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A STUDY OF THE MOUNT ISA ORES.

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ABSTRACT.

A study of a suite of 250 polished surfaces of ores from the Mount Isa mine, Queensland, Australia, reveals, at high magnifications, unusual and interesting replacement structures. The ore minerals are remarkably stratified in sheared and altered slate of pre-Cambrian age. The common minerals are pyrite, sphalerite, galena, pyrrhotite, arsenopyrite, marcasite, quartz, and carbonate in various combinations. Several uncommon minerals are present. Five varieties of pyrite are recognized, of which three were deposited before crushing and shearing of the host rock; the differences are probably due to varying proportions of FeS. Marcasite is derived from pyrrhotite. Oxidation and supergene enrichment processes and products are discussed. The mineralization sequences are: (1) early deposition of pyrite in the slate; (2) crushing and faulting of the pyritic slates and deposition of sulphides of iron, zinc, copper, and lead; (3) oxidation and supergene sulphide enrichment yielding chalcocite, covellite, anglesite, cerussite, jasper, goethite, lepidocrocite. A syngenetic origin for the ore is excluded and an origin by metasomatic replacement is proposed.

INTRODUCTION.

THIS article gives the results of a microscopic examination of over 250 polished specimens from the Mount Isa mine, Queensland, Australia. The authors have not visited the property; the samples were collected by the mine staff. 200 samples came from the main workings, in the Black Star Lode, from the 1st, 2d, 3d, 4th and 5th level, as far as these levels were accessible, and from drill cores 1B, 1C and 1D. The remaining 50 samples were collected throughout the mine. The specimens studied cover a vertical range of 1,400 feet, from the surface downward. In each level samples were taken from the different lodes: pyrite

rib, footwall lode, hanging wall lode, No. 4 and 5 ore body, and as far as possible, the samples on the different levels were taken in corresponding points of these ore bodies.

The extremely fine dissemination of the sulphides in the country rock made high magnification and therefore very careful polishing necessary; the accompanying illustrations show that magnifications as high as 2,000 had to be used. The various minerals were determined exclusively by their color, hardness, shape, internal reflexion and optical properties. Etching was resorted to only in order to develop internal structures, especially for isotropic and weakly anisotropic minerals. Thirty thin sections gave but little additional information, but made possible the determination of some of the transparent minerals.

A more detailed description of some of the most interesting replacement structures will be given by the junior author in a future publication, shortly to appear.

GENERAL FEATURES.

The orebodies occur in a series of steeply tilted, sheared and folded, silicified and carbonated shales of presumably pre-Cambrian age, and the different lodes worked and drilled are closely associated with well defined zones of shearing, which on the whole follow approximately the dip and strike of the sediments.

Granite outcrops and significant quartz concentrations are found within a few miles of the mines.

The ore bodies dip steeply with the strata, but since the shear zones cut the stratification at an acute angle, the tendency of the orebodies is towards an *en échelon* arrangement.

The lodes vary in width from a few feet to 250 feet, and have been exposed along the strike for over 2,000 feet; drilling has disclosed the ore to a depth of 1,400 feet below the outcrop.

MACROSCOPIC STRUCTURES AND TEXTURES.

One of the most characteristic features of the ore is its pronounced schistosity, not only in the weakly mineralized slate, but also in the massive sulphide ore, where replacement of the slate has been complete.

The sulphide layers consist of very fine grained mixtures of the various sulphides, which occur in grains ranging between 1 and 0.001 mm. The layers are rarely thicker than 2 or 3 cm. (Fig. 16) and may even be only a fraction of a (Fig. 14) millimeter. The stratification of the ore minerals is so perfect, down to the minutest detail, that one's first conclusion is of a syngenetic sedimentary origin. Examination of the microscopical structures, however, leaves no doubt as to an epigenetic origin.

The most common mineral combinations in the ore layers are pyrite-sphalerite, sphalerite-galena, sphalerite-galena-pyrrhotite, pyrite-pyrrhotite, quartz-carbonate-sphalerite-galena, and the various silicate minerals of the slate, which have escaped replacement or have been recrystallized during the mineralization process. Concentrations of pyrite-chalcopyrite are found in some parts of the mine.

Surface oxidation has not obliterated the stratification of the ore: hydrous iron oxides, jasper, quartz, cerussite and anglesite show, in the upper levels, the same layered structure as the primary sulphides of the lower levels.

Prior to and during mineralization the slate country rock has been sheared, broken, folded, faulted and in places finely crushed (Figs. 3, 6, 15, 19, 21). Fault movement as a rule does not exceed a couple of millimeters, but crushing and faulting is widespread and has evidently facilitated access of mineralizing solutions. For mineralization of unfaulted fissures see Fig. 8.

The different layers of mineralized country rock may behave differently; whereas layers consisting mainly of slate and pyrite are traversed by clean breaks and faults, the adjoining layers with sphalerite, galena, carbonate and quartz may have suffered only slight folding (Figs. 19, 21).

In places the sphalerite-galena-carbonate layers are microscopically strongly folded, whereas the adjoining pyrite-slate layers are entirely undisturbed (layers 3–7, Fig. 4). This makes it probable that movement also took place along bedding planes and that the more plastic mixture of the sulphides mentioned behaved differently from the brittle and hard pyrite-slate rock.

Figs. 1–13.

Fig. 1. Layers of coarse and fine-grained pyrite alternating with carbonate and columnar pyrrhotite.

Fig. 2. Carbonate with slate layers, veined and impregnated by galena and some sphalerite, pyrite, chalcopyrite, and pyrrhotite.

Fig. 3. Layers of fine-grained pyrite alternating with slate. Slight faulting.

Fig. 4. Black Star mine. Spec. Gl. No. 2 level. *a*, Alternating layers of slate with fine-grained pyrite and sphalerite; *b*, Coarse intergrowth of quartz, sphalerite, galena, carbonate and pyrite; *c*, Mainly sphalerite with residual gangue, and pyrite layers. Partly in fine intergrowth with galena; *d*, Same as *a*; *e*, Oblong irregular sphalerite blebs along stratification plane in gangue; *f*, Same as *c*, with residuals of folded gangue and pyrite layers.

Fig. 5. Stratified ore. *a*, Fine grained shale with a layer of pyrite partly replaced by chalcopyrite or galena; *b*, Pyrite, gangue and chalcopyrite; *c*, Fine-grained sparsely mineralized with pyrite or pseudomorphic chalcopyrite; *d*, Fine-grained dense pyrite and gangue, partly replaced by chalcopyrite; *e*, Dense pyrite with gangue, galena, and traces of chalcopyrite. Part *c* is crossed by several fissures, filled with chalcopyrite, quartz, carbonate, silicate laths and some pyrite and arsenopyrite.

Fig. 6. Strongly faulted and broken layers of gangue with pyrite. Cross fissures and blebs of galena with a little quartz, carbonate, pyrrhotite, sphalerite and chalcopyrite.

Fig. 7. Stratified oxidized ore, mainly anglesite, gangue and quartz; specimen partly etched with Na_2S, thereby converting anglesite into galena to give relief.

Fig. 8. *a*, Gangue veined with galena, high proportion of silver minerals, a little sphalerite; *b*, Galena with quartz end carbonate residuals, pyrite and a few arsenopyrite crystals.

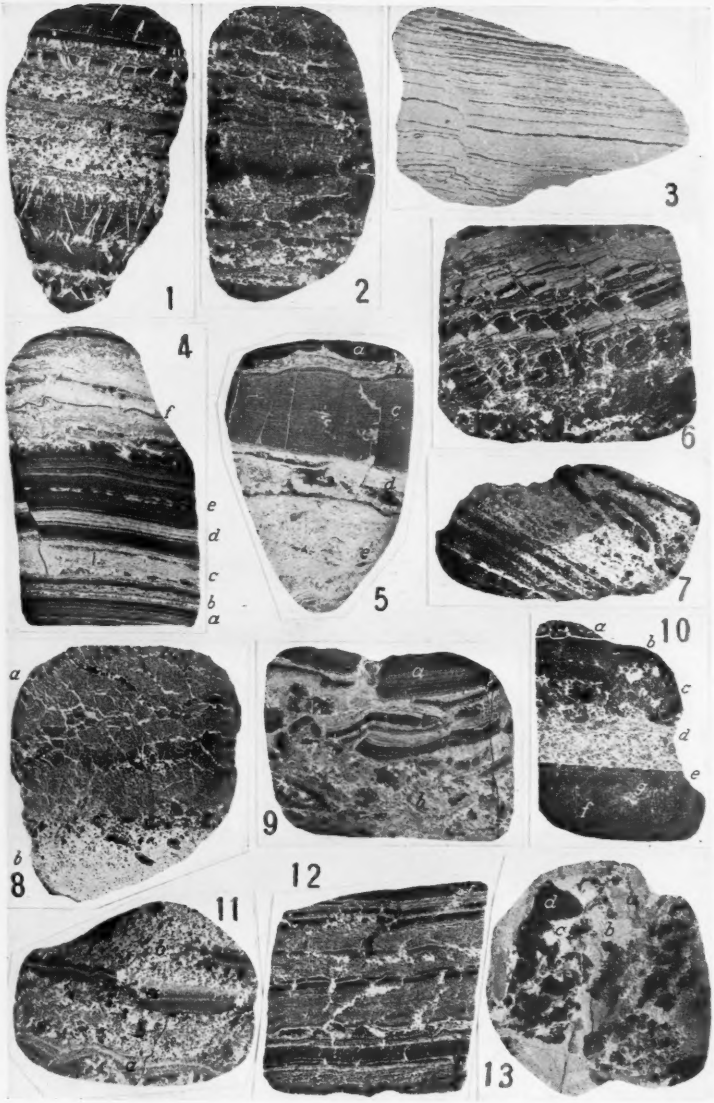
Fig. 9. *a*, Layers of gangue and fine-grained pyrite. Cross fissures with sphalerite; *b*, Mainly sphalerite and galena, with residuals of gangue, replaced partly by sphalerite and galena.

Fig. 10. *a*, Gangue with fine pyrite layers; *b*, Fine-grained gangue with sphalerite, galena and pyrite crystals; *c*, Coarse carbonate, quartz and fine-grained gangue with galena, sphalerite and tetrahedrite; *d*, Coarse galena, quartz and carbonate, with large pyrite crystals, and enclosed residuals strongly impregnated with galena. Gradual transition from 3 to 4; *e*, Fine gangue and pyrite layers; *f*, Very fine-grained gangue (mainly carbonate) with fine sphalerite and galena specks; *g*, Very coarse carbonate with coarse galena, chalcopyrite, tetrahedrite and sphalerite grains.

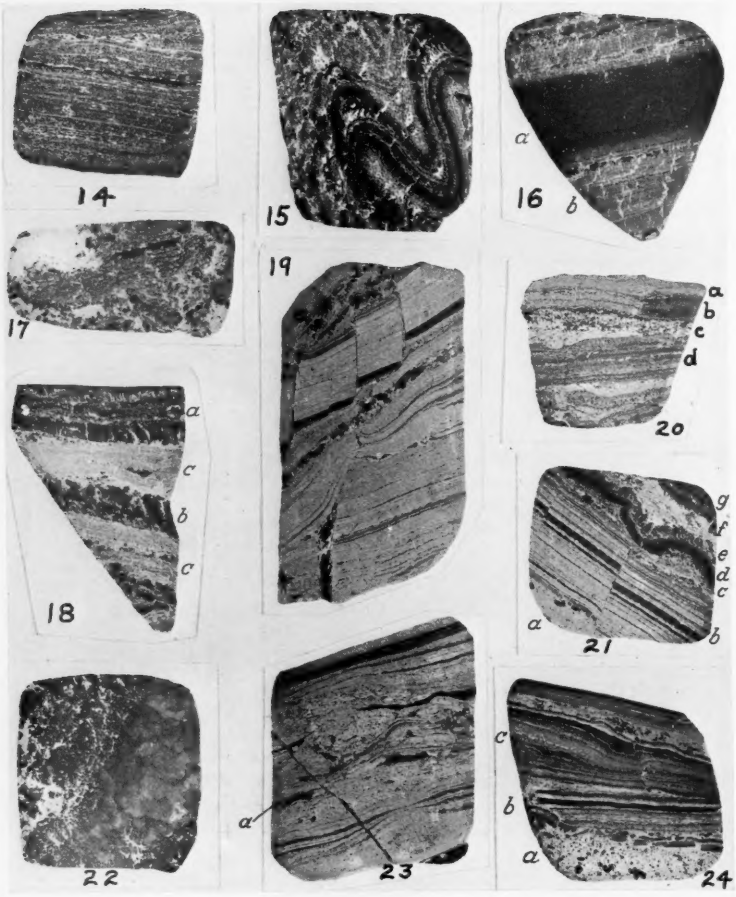
Fig. 11. *a*, Fine-grained gangue, strongly and finely veined with galena and sphalerite; *b*, coarse mixture of galena with quartz and sphalerite. Enclosed residuals of gangue, quartz, carbonate and shale, partly replaced by sphalerite and galena.

Fig. 12. Stratified and fractured ore. Silicified slate with pyrite and galena. Fissures are filled with galena (white), quartz (black) and a little pyrrhotite and sphalerite.

Fig. 13. No stratification; *a*, sphalerite; *b*, galena; *c*, pyrrhotite; *d*, penninite.



FIGS. 1–13.



FIGS. 14–24.

FIGS. 14–24.

FIG. 14. Natural size. Fine-grained and mixed; layers 0.02 to 0.5 mm. thick consist of intergrowths of gangue with sphalerite, pyrite, pyrrhotite and galena. Gangue rich in carbonate.

FIG. 15. Stratified and strongly folded. Veined and impregnated with sulphides; two or three superimposed saddle veinlets.

FIG. 16. Fine carbonated shale between two mineralized layers; *a*, contains many specks of carbonate, partly replaced by sphalerite; *b*, Coarse and fine layers of gangue with sphalerite, galena, carbonate and quartz, which follow bedding plane for short distances.

FIG. 17. Stratification of gangue and pyrite faintly visible; layers almost completely replaced by chalcopyrite.

FIG. 18. *a*, Alternating layers of gangue (mainly quartz) with sphalerite and thin layers of graphite with a little galena; *b*, Coarse mixture of carbonate, quartz and galena; *c*, Coarse and fine intergrowth of galena, sphalerite, pyrrhotite, and carbonate.

FIG. 19. Fine-grained pyrite, stratified. Part *a* is an intergrowth of quartz, carbonate, shale, sphalerite, galena, chalcopyrite and a little pyrite. Strongly broken and faulted. Faults not distinguishable in part *a*.

FIG. 20. Layers of fine-grained pyrite with gangue, sphalerite, pyrrhotite and galena; *a*, Mainly fine pyrite; *b*, Idem. Part of this layer contains no pyrite; *c*, Pyrrhotite with idiomorphic pyrite crystals, sphalerite and galena; *d*, More gangue and sphalerite.

FIG. 21. *a*. Mainly mixture of sphalerite with galena, gangue and pyrite residuals; *b*, Layers of pyrite and gangue with disseminated sphalerite; *c*, Coarse mixture of carbonate and quartz with sphalerite, galena and chalcopyrite; *d*, Fine-grained gangue; *e*, Coarse-grained carbonate and sphalerite; *f*, Coarse mixture of sphalerite, chalcopyrite, galena, carbonate and pyrite cube; *g*, Fine-grained gangue and pyrite. Pyrite and gangue layers faulted. In the other sulphides these faults are no longer visible.

FIG. 22. Mainly ankerite or ferriferous dolomite, veined with pyrrhotite, chalcopyrite with a little pyrite and sphalerite.

FIG. 23. Fine-grained pyrite, alternating with shale layers. Locally the pyrite is in lenses of coarser grains. Some gangue layers partly replaced by pyrrhotite (layer 1). Fissure filled with quartz, carbonate, pyrrhotite, sphalerite and galena. In pyrite and shale layers fine-grained sphalerite is always present.

FIG. 24. *a*, Intergrowth galena-pyrrhotite with enclosed gangue residuals, which are impregnated with sphalerite and galena; *b*, Layers of galena, sphalerite, and pyrite with a little gangue, pyrrhotite and tetrahedrite. Much of the galena has replaced pyrite; *c*, Alternating layers of gangue, pyrrhotite or sphalerite.

Torsional movements are to be observed in Fig. 4, left side; layers 1 and 2 are undisturbed, layers 3, 4, 5 and 6 have suffered differential movement, increasing with distance from the borderline between b and c. Rarely the mineral mixture has been so thoroughly broken and kneaded together, that reconstruction of the original structure is difficult (Fig. 9).

Proof for metasomatic processes as the principal agents in the genesis of the ore will be brought forward in the following pages, but even a macroscopical study of the ore gives sufficient indication of this. A few examples will suffice: The right side of layer 2 in Fig. 20 consists of pyrite with a little sphalerite and gangue, the left side is gangue with sphalerite. The transition between these two halves is very gradual; the layers above and below contain pyrite over the whole length.

A clear illustration is also furnished by Fig. 23, where the gangue layer on both sides of fissure 2 has been replaced across a width of a couple of millimeters by pyrrhotite, which also fills the fissure. Fig. 4 shows clearly stratified ore; in parts 3 and 7, consisting mainly of sulphide, replacement remnants of enclosed country rock are visible. A similar occurrence is shown in much disturbed ore in Fig. 9. Layer a in Fig. 11 gives a clear picture of metasomatic replacement; the lowest of the three layers and the upper part of the central layer are light colored owing to the advanced replacement by galena. In Fig. 10, the gangue remnants decrease from 4 to 3. As will be seen later, microscopic replacement structure in this instance is also convincing. In Figs. 8 and 22 replacement starts from innumerable thin cracks; slate residuals are clearly visible in layer 4 of Fig. 5. The center of Fig. 17 consists of fine layers of slate and fine-grained pyrite. In the rest of this specimen these layers are almost completely replaced by chalcopyrite.

These examples of macroscopic structures will be supplemented by a description of microscopic structures, which will give definite proof of metasomatic replacement in Mount Isa ores.

MICROSCOPIC TEXTURES.

The most common mineral combinations are:

a. Slate layers more or less carbonated and silicified with little or no sulphide. Part 1, Fig. 16.

b. Slate more heavily pyritized, with varying amounts of sphalerite. The pyrite occurs as little spheres (Fig. 25) crystals (Fig. 65) or as ring shaped particles which will be discussed in more detail below. Sphalerite is either absent or has replaced the pyrite to such an extent, that only sphalerite remains (Fig. 50).

c. Slate with pyrite, chlorite or mica remnants (Figs. 30, 37, 117). The last photo shows clearly the stratification.

d. Layers of carbonate-rich slate, with pyrrhotite individuals of varying dimensions. Pyrrhotite in places replaces the slate completely, and the result is a layer of pure pyrrhotite. If the slate contained abundant early pyrite, this pyrite is surrounded and not replaced by the pyrrhotite (Fig. 55).

e. Layers of a special sphalerite-galena intergrowth. Fig. 27 shows galena inclusions in the sphalerite, oriented parallel to original stratification. In places these galena blebs are found 2 cm. long by 0.0025 mm. thick, stretched parallel to the stratification. A common structure is shown in Fig. 38.

f. Layers of pyrrhotite and galena with gangue- and sphalerite-residues. The pyrrhotite is partially replaced and rounded (Fig. 36). It is likely that this structure is due to replacement by galena of a pyrrhotite-sphalerite-gangue intergrowth, where the two last minerals have suffered most.

g. Layers of sphalerite with beautifully shaped pyrite crystals and gangue residuals. Pyrite partially replaced by sphalerite.

h. Slate or other gangue with innumerable specks of galena (left and right part of Fig. 93, also Fig. 34). Fig. 29 shows such an abundance of galena, that it forms complete layers, crossed by galena-filled fissures.

i. Layers of galena, pseudomorphous after pyrite, in a groundmass of slate, carbonate or sphalerite.

j. Layers of very fine grained to coarse pyrite, imbedded in galena. Resulted from the replacement by galena of the minerals in which the pyrite crystals were enclosed. Pyrite crystals partly corroded. In Fig. 28 the first phase of this process is shown, where pyrite has not yet been attacked; the deposition of fresh coarse quartz with the galena is also apparent. Fig. 76 shows curiously shaped pyrite replacement residuals.

k. Layers with irregular intergrowths of various minerals such as quartz, carbonate, sphalerite, galena, pyrrhotite and a little chalcopyrite. (Fig. 29.)
With the exception of the fairly pure pyrite, galena or sphalerite, these intergrowths are exceedingly fine grained, diameters varying between 0.05 and 0.005 mm.
Coarse grained mixtures are found in:

l. Layers and veinlets of sphalerite, galena, pyrrhotite, quartz and carbonate, with grain size up to 2 mm. See layers 5 and 6 Fig. 21, layers 2 and 3 and layer between 6 and 7 in Fig. 4.

m. Pure galena layers with gangue remnants (4 Fig. 10, 1 Fig. 24).

Filling of cross fissures nearly always consists of either the *l* or the *m* variety.

A few special features warrant a short description:

Along the 6422 N coördinate of the Black Star mine, ore rich in chalcopyrite and carbonate is found. Stratification has practically disappeared. The gangue is traversed in all directions by numerous irregular veinlets of various sulphides. (Fig. 22.) Wherever chalcopyrite is abundant, it takes the same place as sphalerite and galena in the other ore (Figs. 5 and 96). Massive pyrite is much fractured. Several fissures perpendicular to the stratification, filled with quartz and carbonate cross the pyrite. Fig. 40 showing one of these fissures with the crystals of the

quartz-carbonate filling oriented perpendicular to the walls suggests the filling of an open fissure; pyrite fragments are absent.

Figs. 15 and 33 show structures in relation with folding. In places a thin layer is strongly folded whereas the adjoining layers have not been affected.

Fig. 53: A fissure has opened alongside the fold, which is shown by Fig. 15, and has been filled with a gangue-free mixture of galena, pyrrhotite and tetrahedrite. Dimensions of the fissure are 15 mm. by 0.0025 mm.

DESCRIPTION OF MOUNT ISA MINERALS.

Pyrite. According to their shape and mode of occurrence, five different kinds of pyrite can be distinguished:

a. Very fine-grained "spherical pyrite," grain size 0.025 to 0.005 mm., mostly with concentric zonar structure.

b. Fine grained pyrite in clean cut crystals, idiomorphic or idioblastic. Grain size 0.02 to 0.005 mm. Variety *a* may pass into *b*.

c. Very fine-grained pyrite with skeleton-like shapes, mostly smaller than 0.01 mm.

d. Coarse-grained pyrite in sphere-like aggregates or in spherolitic concretions, 0.25 to 0.05 mm.

e. Coarse-grained aggregates or fragments of crystals, size 0.5 to 0.05 mm.

Variety *a* belongs with *b* and *c* to the oldest generation of pyrite, and occurs mostly in layers, alternating with gangue or with other sulphides. It is found also in fragments of layered ore, imbedded in younger sulphides. It never fills the tiny fault fissures and cracks, and it certainly is older than the period of crushing and faulting. Figs. 25 and 62 show this pyrite, always intergrown with gangue and in places with fine sphalerite. The thickness of the layers varies between 20 and 0.05 mm. Strong magnification reveals a more or less spherical shape, which generally passes gradually into a square or a hexagon—a transition to the *b* crystals.

Even without etching, a lack of homogeneity in the structure is faintly visible; etching with nitric acid shows a marked difference between core and shell (Fig. 63: pyrite in gangue; Fig. 62: same pyrite after etching). In places the core is spherical, but generally a spherical pyrite grain is built up around a well crystallized core.

Where the outer shell increases in width, etching reveals a faint radial fibrous structure. Resistance to etching varies, sometimes the core is more readily attacked, sometimes the shell.

These pyrite grains with their uniform grain size and shape bear a marked resemblance to the pyrite of Meggen, Rammelsberg, and Mansfeld, described by Frebold, Ramdohr and Schneiderhohn. These authors conclude that this sulphide has a sedimentary syngenetic origin. Under the heading "Genesis of the ore" this theory will be discussed; in the meantime it may be of interest to point to a few differences between the Mount Isa pyrite and that of the German occurrences.

FIG. 25. Alternating layers of fine-grained shale and spherical pyrite. A few sphalerite specks. × 65.

FIG. 26. Fine layers of gangue (dark) gray sphalerite, white pyrite with high relief, some pyrrhotite and galena. A sphalerite-galena veinlet crosses the layers. Pyrite crystals are partly pseudomorphosed by galena. × 65.

FIG. 27. Layers of dark gray gangue, gray sphalerite, and sphalerite-galena (white). The form of intergrowth sphalerite-galena reveals the original stratification. Sphalerite does not conform to the layers, but crosses them. × 35.

FIG. 28. Galena replacing gangue- and pyrite-layers. × 35.

FIG. 29. Gangue layers with gray sphalerite and white galena. The gangue mass and pyrite specks are largely replaced by galena. × 35.

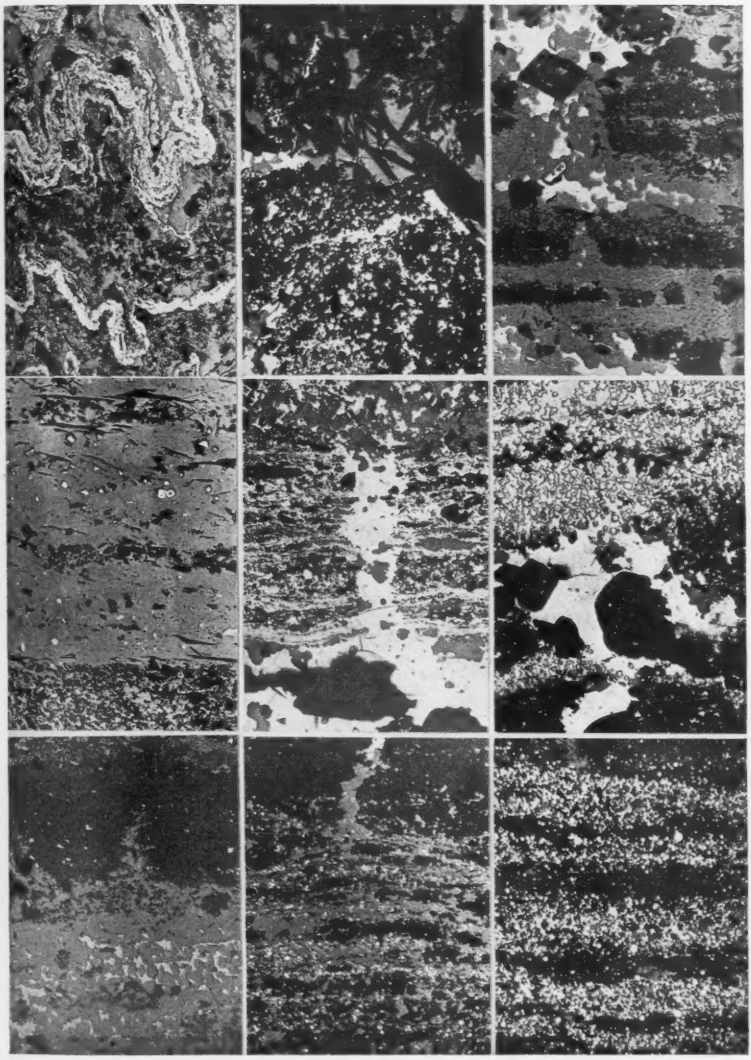
FIG. 30. Last residue of gangue with chlorite laths in sphalerite. White crystals with high relief; pyrite, without relief; galena. × 35.

FIG. 31. Sphalerite and galena break through residuals of gangue layers. Irregular dark quartz grains, light gray, rhomb shaped, carbonate; pyrite, partly replaced by sphalerite. × 35.

FIG. 32. Difference in replacement structure of same gangue by sphalerite and galena. × 65.

FIG. 33. Strongly folded and kneaded layers. Dark gray gangue, gray sphalerite, light gray to white; kneaded mass of sphalerite and galena with gangue and carbonaceous matter. × 35.

25 26 27



28 30

31 32 33

FIGS. 25–33.

The latter consists generally of aggregates of a large number of small grains or they have a radial fibrous structure throughout, whereas the Mount Isa variety shows a massive core, surrounded by concentric layers. Another distinct feature is that the pyrite in the German deposits is generally accompanied by marcasite, which is nearly absent in the samples from the Black Star mine.

Variety *b*, idiomorphic crystals, forms separate layers with gangue, but, as stated above, in some instances occurs together with *a* variety. Fig. 65 shows the *b* pyrite, forming layers rich in pyrrhotite and sphalerite, which have partly replaced the pyrite.

This pyrite is generally pure and rarely contains inclusions. An exception must be made for metasomatic alterations by the younger sulphides, to be described below.

Variety *c* is shown in Fig. 110: skeleton crystals, single or in aggregates, in places intergrown with galena in gangue. This variety belongs with *a* and *b* to the earlier pyrite, but occurs only sporadically. The most common shapes are crosses or stars. Galena occurs in the center of the skeletons or between the ribs of the stars.

Fig. 110 shows the first stage of the replacement process. Galena replacement may continue and fill the interstices between the ribs, and the result is a square of galena with diagonal pyrite

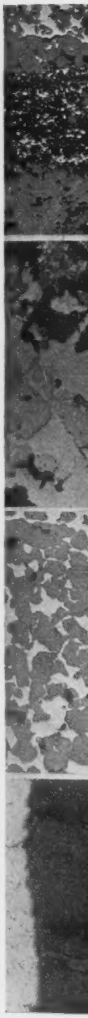


FIG. 34. Residuals of gangue in sphalerite and galena. Galena in gangue pseudomorphic after pyrite. × 30.

FIG. 35. Difference in replacement structure of coarse and fine-grained carbonate by chalcopyrite. Dark gray quartz with high relief is not replaced by chalcopyrite. In coarse carbonate chalcopyrite is coarse, in fine grained carbonate it is fine. × 30.

FIG. 36. Intergrowth of pyrrhotite (light gray), white galena, and dark gray gangue, × 60.

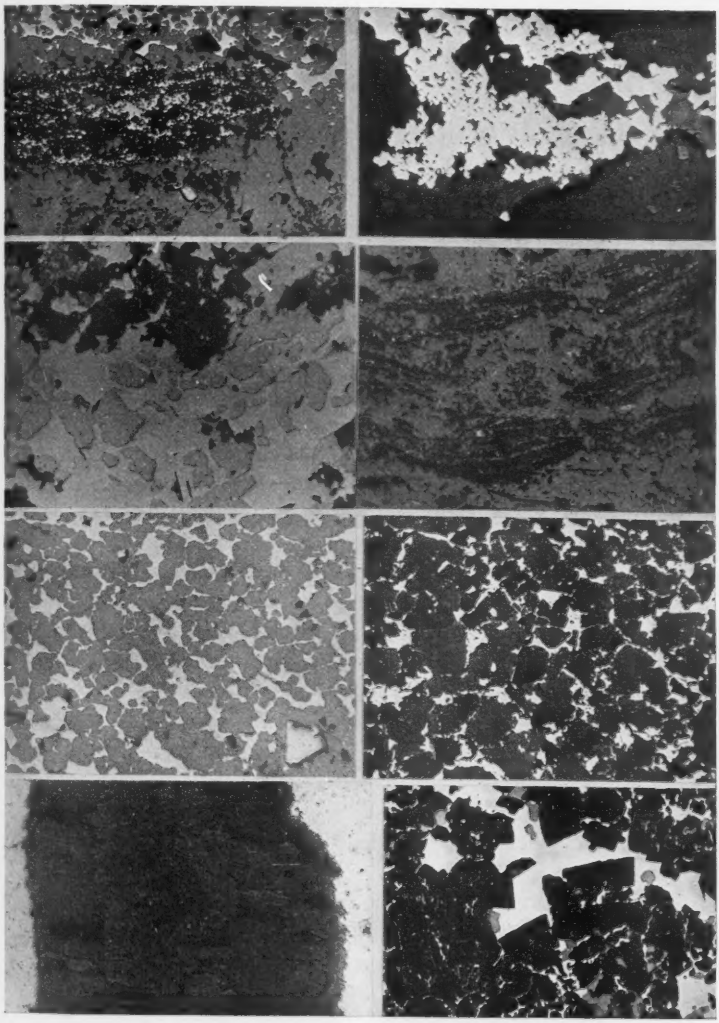
FIG. 37. Gangue residuals in sphalerite. Fine white galena specks in gangue pseudomorphic after pyrite. × 60.

FIG. 38. Normal intergrowth of sphalerite and galena. × 60.

FIG. 39. White galena replaces fine grained pleochroic carbonate from grain boundaries. × 60.

FIG. 40. Dark gray, carbonate; very dark gray, quartz; white, pyrite. A quartz carbonate veinlet crosses massive pyrite layers. × 30.

FIG. 41. Replacement of coarse carbonate by galena, leaving carbonate rhombs. × 30.



FIGS. 34–41.

ribs. This intergrowth is rare and seems to be confined to carbonate gangue, which is more easily replaced by galena.

Fig. 67 shows a curious intergrowth of pyrite *d* with galena and sphalerite. Generally the center of the spheres is more porous than the rim, which explains the preferential replacement of the center, as will be shown below. This variety is found in exclusive intergrowth with galena and sphalerite.

Variety *e*, coarsely crystalline, presents several features that distinguish it from the others. The shape of the crystals is seldom as perfect as that of the *b* variety, though just as the latter it occurs mostly in cubes. They commonly form aggregates and are rich in galena and sphalerite inclusions. This pyrite is found mainly with the young sulphides, does not form distinct layers, as does the older pyrite, and it commonly fills fissures and cracks in the older ore. Figs. 48 and 83 show cubic crystals with a tendency toward the building of aggregates.

The bulk of the pyrite is composed of varieties *a* and *b*. They, together with the skeleton variety *c*, are the earliest sulphides, having all been deposited before the main crushing period of the slate set in. This will become clear also from the evidence that will be given in the chapter on metasomatism. The pyrites *d* and *e* have not been affected by the faulting and must be considered posterior to this. They are, however, earlier than the other sulphides, as will be shown below.

It must be concluded that the pyrite arrived in two periods, separated by a fairly long interval: the time that has elapsed between the deposition of the younger pyrite and the younger sulphides is not so clearly marked, although without any doubt all the sulphides of zinc, copper and lead are younger than those of iron.

The pyrite varieties described differ not only in shape and internal structure, but they also show very slight differences in color. These differences might be caused by varying proportions of FeS in the pyrite molecule. (Ehrenberg has shown that, f. i., melnikowite contains a varying content of FeS.) Some of the pyrite varieties in Mount Isa might approach melnikowite in their

chemical composition and these slight variations in chemical compositions, coupled with different internal structures, would go far to explain the remarkable diversity of replacement structures that this ore displays.

Pyrite is replaced by sphalerite, galena, pyrrhotite, chalcopyrite, tetrahedrite and probably by some carbonate. In the outcrop it is transformed into the customary oxidation products, its original structure in many cases being retained. Being the oldest sulphide, it does not replace other sulphides; rarely, a transformation of pyrrhotite into pyrite can be observed.

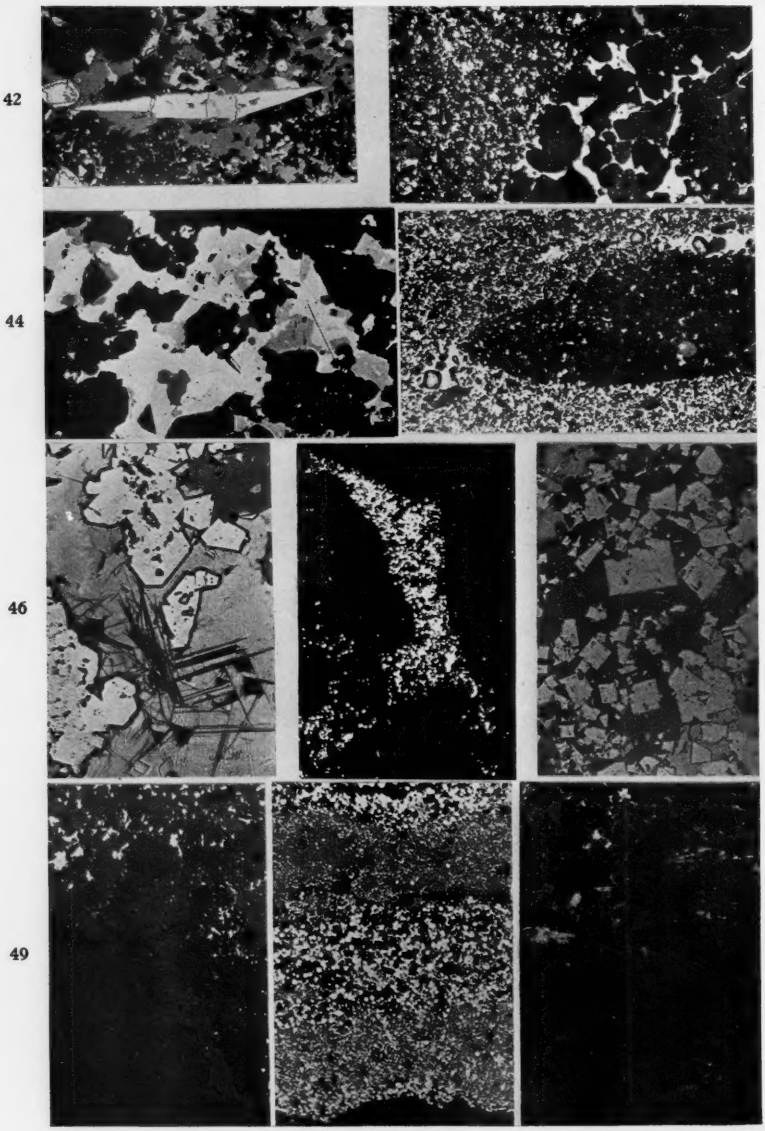
The relations between pyrite and slate are not clear. If they were, there might be a definite solution of the old problem: is the pyrite syngenetic with the sedimentary rock? The extreme fineness of the pyrite grains and the well known ability of pyrite to form idiomorphic crystals even in compact rocks, makes it difficult to determine the age relations in the early history of this deposit. Fig. 47 shows the *a* variety (an early pyrite) intergrown with carbonate in a way that suggests a late deposition of the pyrite: the pyrite points are concentrated in the groundmass between larger carbonate individuals.

Arsenopyrite.—Arsenopyrite occurs sparingly as idiomorphic or idioblastic grains, enclosed in the slate- or pyrite-layers, or in the younger sulphides, either in the layered ore or in the cross fissures. It is earlier than the Pb-Zn-sulphides but younger than the pyrite of the first generation. Where arsenopyrite has developed in the pyrite-rich parts of the ore, the pyrite grains remain undigested as inclusions in the arsenopyrite (Fig. 59).

In Fig. 42 galena has partly replaced an arsenopyrite crystal or cemented its fragments.

Pyrrhotite.—The shape of the pyrrhotite crystals seems to be dependent on the medium in which they occur.

a. In coarse grained carbonate it is found in idiomorphic crystals (Fig. 80). More commonly, the pyrrhotite grains have adopted the straight boundaries of the crystallographic planes of the carbonate or fill irregular fissures through it, or again inherit their structure from the twin-



FIGS. 42–51.

ning lamellæ it replaces (Figs. 112, 116). Grain size 0.2 to 0.05 mm.

b. In slate, whether silicified or carbonated, the pyrrhotite assumes oblong shapes (Fig. 1). Fig. 94 shows an oblong grain, the form of which is probably inherited from the replaced silicate lath.

c. Where pyrrhotite contributed to the filling of a fissure, it generally also penetrated both walls (Fig. 23).

d. It may replace certain sedimentary bands completely, resulting in stretched homogeneous pyrrhotite masses. Fig. 55 shows with stronger magnification the gangue-pyrrhotite boundary of Fig. 23. The original pyrite layers are seen to continue unreplaced in the pyrrhotite. A curious feature of these continuous pyrrhotite bands is that they are

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FIG. 42. White arsenopyrite crystal, broken and cemented (partly replaced?) by galena. Groundmass is gangue with carbonate, quartz (black), sphalerite (gray), pyrite atolls (white), with galena cores. × 60.

FIG. 43. Shows difference in replacement structure between fine grained gangue (carbonated shale) and coarse grained carbonate-quartz mixture, by galena. × 30.

FIG. 44. Galena and chalcopyrite (both nearly white), light gray tetrahedrite, and gray sphalerite, in dark gray carbonate and quartz. × 120.

FIG. 45. Lens of refractory gangue resisting galena replacement. Carbonate and galena specks in lens have same shape. × 60.

FIG. 46. Pyrite crystals (white, high relief), light gray galena, gray sphalerite, chlorite laths and two small arsenopyrite crystals. × 60.

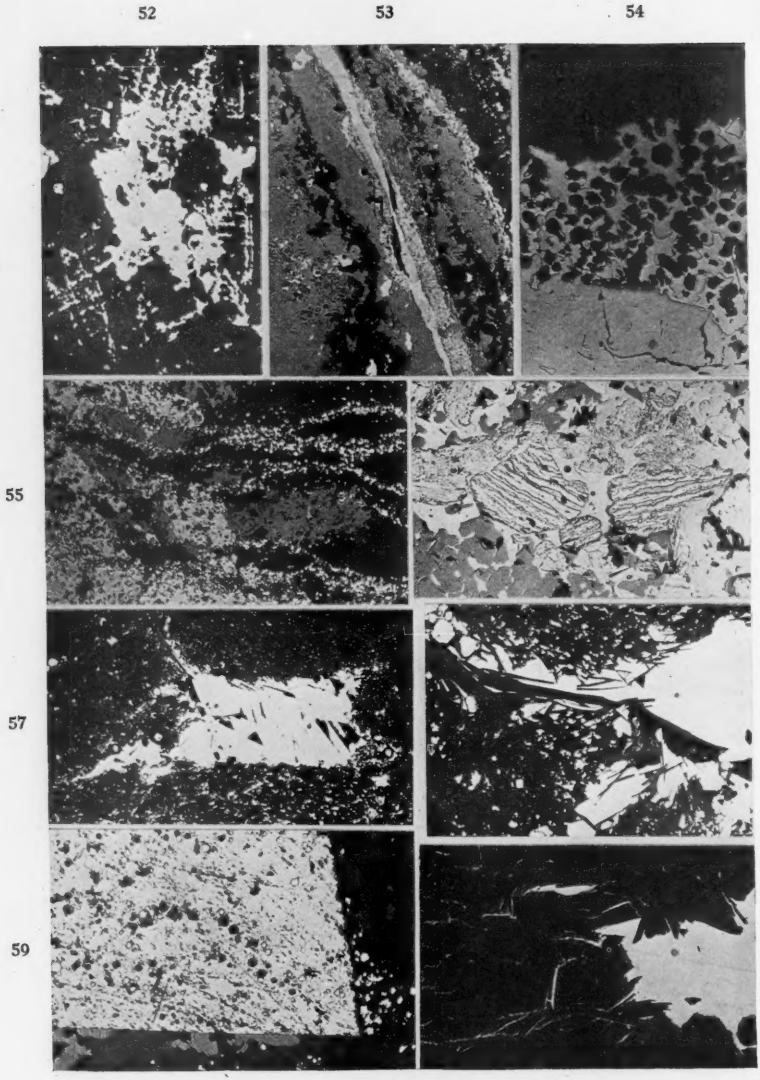
FIG. 47. Spherical pyrite confined to certain spots between carbonate individuals. × 60.

FIG. 48. Idiomorphic pyrite crystals (variety *e*) in gangue (dark gray); galena (very faint gray). × 30.

FIG. 49. Very dark gray quartz replaced by dark gray carbonate; chalcopyrite confined to carbonate. × 30.

FIG. 50. Layers of gangue (dark gray) sphalerite (gray) and pyrite. Pyrite mostly replaced by sphalerite. In other parts of the same specimen layers with pyrite crystals in undiminished size continue undisturbed. × 120.

FIG. 51. Rhombohedral and irregular carbonate crystals in dark gray quartz, lining a carbonate filled veinlet that crosses quartz. White: chalcopyrite and pyrrhotite. × 30.



FIGS. 52–60.

formed by one single crystal as evidenced by the uniform extinction. Pyrrhotite grains of this character, 5 mm. long, are no exception.

e. Pyrrhotite specks, imbedded in sphalerite, chalcopyrite, galena and other late sulphides, are always fine-grained and irregularly shaped and are probably replacement residuals of older pyrrhotite.

The two latest varieties are most common. Pyrrhotite is younger than slate and the older pyrite and the greater part of the carbonate. It is earlier than galena, chalcopyrite and tetrahedrite. Its age relation toward sphalerite is not easy to define; some of the sphalerite seems to be earlier.

Sphalerite.—This mineral is irregular of shape; in slate and carbonate angular inclusions predominate with straight boundaries; in galena, which has replaced it, rounded grains are prevalent. Only sparingly was it seen to adopt straight boundaries parallel to the twin lamellæ of carbonate.

The most common intergrowths of sphalerite are with slate, pyrite, galena, and carbonate-quartz-galena. Only in the last named combination are the grains coarse, 0.2 to 1 mm., otherwise

FIG. 52. Chalcopyrite in replacing carbonate follows two twinning systems. ×120.

FIG. 53. Veinlet which for a few cm. parallels a steep fold in shale (from Fig. 15). Contains tetrahedrite and galena. The walls consist of a fine ground mass of sphalerite, galena and gangue. ×60.

FIG. 54. Light gray pyrrhotite and white galena replace dark gray penninite. ×30.

FIG. 55. Pyrite layers (white) in gangue (dark gray), massive white pyrrhotite (pale gray), sphalerite (gray). Pyrite layers continue undisturbed in pyrrhotite and sphalerite that have replaced gangue.

FIG. 56. Marcasite (white with relief) and galena (between the marcasite shreds) have replaced pyrrhotite. Fine intergrowth of pyrrhotite and marcasite in upper side of photo. ×60.

FIG. 57. Replacement of slate by galena, with silicate laths on the replacement front. See Fig. 58. ×30.

FIG. 58. Part of Fig. 57 highly magnified. ×130.

FIG. 59. Part of arsenopyrite crystal in slate. Pyrite layers continue in crystal. Weakly etched, only carbonate dissolved. ×120.

FIG. 60. Galena replaces penninite. First stage. ×80.

the grains do not exceed 0.1 mm. Etching shows polysynthetic twinning.

Sphalerite, which has replaced coarse-grained carbonate, develops coarse aggregates; on the other hand fine-grained slate and carbonate force their fine structure on the later sulphide. This constant relation is evidently the consequence of metasomatic replacement.

It is younger than the older pyrite and the slate, and older than the vast majority of the other sulphides.

Sphalerite is commonly accompanied by fairly coarse-grained silicate laths, that occur mostly on the boundary of sphalerite and slate. These silicates are not found in the unmineralized slate, and it may be assumed that the zinc-bearing solutions have effected a recrystallization of the slate. We found something like this in the ore of the Sullivan mine of the Consolidated Mining and Smelting Co. of Canada, which on the whole presents several features strikingly similar to those of Mount Isa.

Fig. 117 shows an intergrowth of sphalerite with these silicates from the Black Star mine. These laths are also found lining the walls of sphalerite-filled fissures in the slate, oriented with their long axis more or less perpendicular to the fissure walls.

Galena.—As has been shown by Figs. 8, 10, 11, 18 and 24, galena may form layers of appreciable thickness in the slate and it can fill cross fissures. In places, replacement of slate by sulphides and mutual replacement of sulphides has been so energetic that the original parallel structure has disappeared (Figs. 24, 11, 10, 8). Filling of fissures is shown by Figs. 2, 8, 12, and 19.

Galena may replace pyritized or carbonated slate, resulting in fine impregnations (Figs. 93, 57, 58). In pyritized slate in some instances the pyrite is preferentially replaced by galena, in others the pyrite is spared and is found imbedded in the galena. Galena is one of the latest sulphides: it replaces pyrite, pyrrhotite, sphalerite, chalcopyrite, carbonate and slate.

Chalcopyrite.—This mineral is found only sparingly in the lead-zinc ore, but in some parts of the deposit it dominates, where lead and zinc are less conspicuous. An example of this is found

in the deep level along the 6422 North coördinate, Black Star mine, where a pyrite-chalcopyrite ore is found, low in lead and zinc, but richer than normally is the case, in iron-bearing dolomite or ankerite. It rarely forms complete layers, as do pyrite, galena and sphalerite, but mostly occurs as irregular blebs and in veinlets across slate (Figs. 5 and 17) or sulphides (Fig. 22).

As far as can be judged from the samples examined, it seems that in general chalcopyrite is accompanied by carbonates, whereas pyrrhotite is generally found in quartz gangue.

Chalcopyrite, replacing slate, carbonate, quartz, pyrite, pyrrhotite and sphalerite (Fig. 99) shows a great variety of replacement structures. Chalcopyrite, also, is accompanied by newly formed silicate crystals, as has been stated for sphalerite. Chalcopyrite in slate is irregularly shaped; in carbonate the structure inherited from the host mineral may give the appearance of idiomorphic crystals. Between crossed nicols it shows a coarse-grained texture with lamellar twinning.

Tetrahedrite, and Silver Minerals.—Tetrahedrite is the only silver-bearing mineral, found in the Black Star mine. Proustite and polybasite occur sparingly in other lodes. Tetrahedrite was found in most samples from No. 1 Panel of the Footwall Lode and in various samples from No. 4 and 5 Orebody, and from drill holes 1 B, 1 C and 1 D. It does not occur in the 1st and 2d level or in the Scram drive pyrite. In general, it tends to be absent where the older pyrite or the sphalerite are abundant. As it is one of the latest sulphides, it has followed the channels that sewed the younger sulphides and is found accompanying these (Figs. 21, 4, 24, 18, 10 and 8). Fig. 44 shows a spot particularly rich in tetrahedrite. The mineral always occurs in irregular blebs, intergrown with galena or chalcopyrite.

Valleriite.—This rare nickel mineral, conspicuous by its strong double refraction[1] and anisotropism, has been described by Ramdohr and Schneiderhohn. Buerger mentions it in the Frood mine and from Prince William Sound in Alaska. The authors found it also in ores from Sulitelma, Roros, Witwatersrand, cop-

[1]The term double refraction seems to be better than reflex-pleochroism (as shown by Berek).

per ores from Mozambique, and in gold ore from Surinam. The unknown nickel ore, described by Schneiderhohn from Mooihoek, Transvaal, is probably also valleriite.

In the Mount Isa ore it occurs as very minute laths, stars and wormlike grains in chalcopyrite. Until now it has been found only in the Hanging Wall Lode drillhole 1D. Grain-dimensions: 0.05 to 0.005 mm. by 0.002 to 0.0005 mm.

Jamesonite.—This mineral occurs sporadically in small oblong grains enclosed in galena.

Pentlandite.—This nickel mineral was found only in one specimen from H. 40 stope Black Rock mine, straddling a tiny fissure in pyrrhotite. (Similar occurrence in the ores from Sudbury and Evje.) The mode of occurrence suggests that it is younger than the pyrrhotite.

Marcasite.—Marcasite is exceedingly rare and the primary origin of even the rare specimen is doubtful. It is well known that both hypogene and supergene solutions can transform pyrrhotite into marcasite. Three varieties of marcasite can be distinguished:

a. Minute laths, 0.01 to 0.002 mm. by 0.001 to 0.002 mm. were found with the skeleton pyrite, mentioned above. This variety is very scarce, and, owing to its fine grain is difficult to determine.

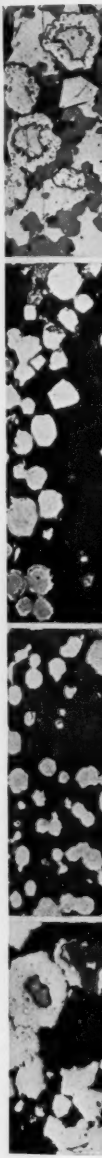


FIG. 61. Dark gray carbonate, gray sphalerite, white pyrite (high relief), white galena. Atoll shapes of pyrite and galena, due to replacement. × 72.

FIG. 62. Etching structure of older spherical pyrite. Either the rim or the core is more easily etched. × 320.

FIG. 63. Spherical pyrite (variety *a*) and crystals (variety *b*) in shale. × 410.

FIG. 64. Atoll shaped intergrowths of gray sphalerite and white pyrite in dark gangue. Pyrite crystals partly replaced by galena. × 320.

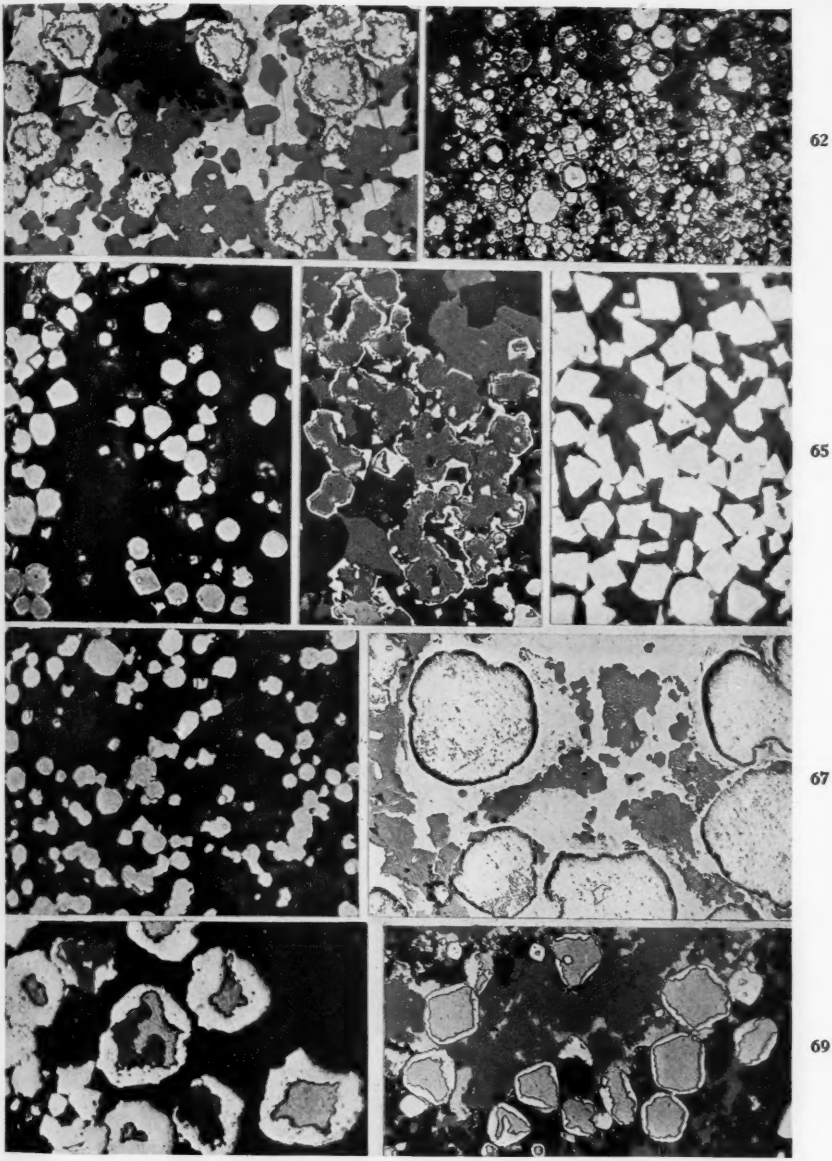
FIG. 65. Pyrite crystals (variety *b*) in dark gangue. × 630.

FIG. 66. Chalcopyrite pseudomorphic after spherical pyrite. × 360.

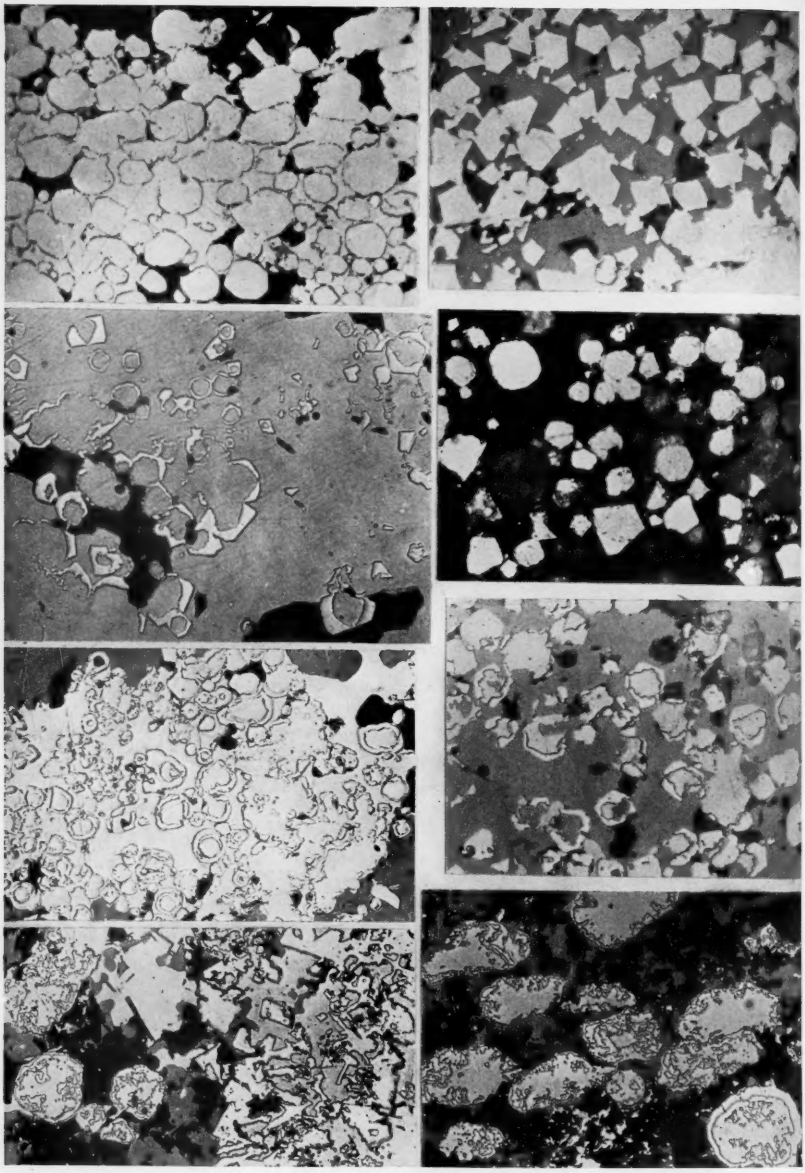
FIG. 67. Spherical pyrite in intergrowth of sphalerite and galena. Galena replaces sphalerite at its contact with pyrite. × 72.

FIG. 68. Part of Fig. 76 strongly magnified. × 360.

FIG. 69. Atolls of pyrite (white) with galena cores (light gray) surrounded by sphalerite and gangue. × 320.



FIGS. 61–69.



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72

74

76

FIGS. 70–77.

b. Normal marcasite, as metasome after pyrrhotite, in bundles of thin laths, lying parallel to 001 of pyrrhotite, and in instances separated by layers of galena. Fig. 56 shows this structure, caused probably by hypogene solutions which transformed the pyrrhotite in galena and marcasite. This variety was found in a vertical range of 300 to 700 feet, surrounded by entirely fresh sulphides, which precludes the possibility of supergene action.

c. Doubtful variety, described by Ramdohr and Schneiderhohn in their textbook "Lehrbuch der Erzmikroskopie." The mineral is without lustre and difficult to polish and was found only in the No. 1 level, 50 meters below the surface, in ore, poor in pyrite, but rich in sphalerite, galena and pyrrhotite. It is probably due to supergene action, which has transformed the pyrrhotite into marcasite. All the pyrrhotite grains that show this alteration, are surrounded by a narrow rim of anglesite. The marcasite is found in pyrrhotite only alongside cracks, which, when they cross galena, are lined with anglesite.

Graphite.—Graphite is generally taken to be formed at rather high temperature or pressure, in pegmatitic-pneumatolytic ores or in contact metamorphic deposits. The presence of graphite in the Mount Isa ore is therefore of interest, not only because it has

FIG. 70. Aggregate of galena spheres (white), pseudomorphic after pyrite. Black is slate. Note dark rim around galena spheres. × 800.

FIG. 71. Galena (white) pseudomorphic after pyrite crystals in sphalerite (gray). One pyrite residual (white). × 500.

FIG. 72. Atoll-shaped residuals of idiomorphic pyrite (white) in gray chalcopyrite. × 500.

FIG. 73. Galena (white with black central points) and dark gray sphalerite, both pseudomorphic after pyrite spheres. White, pyrite. × 800.

FIG. 74. Pyrite rims and other residuals in galena. Gray sphalerite. See Fig. 98. × 350.

FIG. 75. Pyrite atolls, with galena and sphalerite cores. × 500.

FIG. 76. A layer of atolls in slate. Rim is pyrite. Core is galena or galena and sphalerite. × 90.

FIG. 77. Residuals of irregular atolls, pyrite rims and galena cores. In gangue and sphalerite. × 90.

probably been formed at no high temperature, but also because here it occurs in a form, which until now, we believe, has not been described.

In the Mount Isa ores graphite surrounds pyrite grains in radial-fibrous shells, and the same shells are found broken and torn apart in carbonate, sphalerite or galena. It occurs also in small blades or laths in sphalerite. Radial cracks in these shells are generally filled with galena (Figs. 103, 104, 105 and 92). The mineral shows very strong double refraction; on revolving the stage, it is alternatively much darker and lighter than sphalerite.

Galena grains, pseudomorphous after pyrite, are in many cases rounded by a dark-colored rim. Although the identity of this material could not be established with certainty, it is believed to be graphite. Graphite is younger than pyrite and older than all the other sulphides. Its rare occurrence and the small dimensions of its grains make any conclusion as to its origin difficult.

Electrum and Gold.—Only once a small speck of gold was found in the outcrop ore imbedded in jasper and hydrated iron oxide. A few very minute specks of electrum were determined in the drill cores from the deepest levels, always in galena with tetrahedrite.

Unknown White Mineral.—This mineral occurs sporadically in perfect idiomorphic crystals, always enclosed in galena or quartz and generally accompanied by arsenopyrite and pyrrhotite (Fig. 115). The cross section perpendicular to the main axis is a rectangle with blunted edges. Hardness is higher than galena, lower than arsenopyrite and about equal to that of sphalerite or pyrrhotite. It shows strong double refraction in oil from white to pinkish brown, and is strongly anisotropic. Although it resembles some of the known minerals, it could not be determined.

Rutile.—Rutile must be regarded as an original constituent of the slate, perhaps recrystallized during the sulphide mineralization. Undigested residuals are found in galena.

Gangue.—The country rock is exclusively a black slate, gen-

erally either silicified or carbonated. It is not possible to establish whether the quartz and carbonate were original constituents of the sediments, but in many instances the filling of fissures and the impregnation of its walls by carbonate and silica suggest that they both took part in the later mineralization. Under the heading "Sphalerite" the recrystallization of slate substance to coarsely crystalline silicates such as mica, chlorite, zoisite, and penninite was mentioned (Figs. 116 and 46). These silicates resist the subsequent replacement processes, although in places pyrrhotite and galena penetrate and slightly replace them (Figs. 54 and 60).

Carbonaceous matter may be abundant; this would explain the formation of graphite by recrystallization.

A minor constituent of the slate is rutile in small aggregates or slender prisms.

Supergene Processes and Minerals.

A study of polished surfaces reveals that in general the bottom of the zone of oxidation runs parallel to the surface at a depth of approximately 250 feet. As was to be expected, the effect of oxidation has been stronger in the pyrite-rich and in the steep lodes. The layered structure has been remarkably well preserved and the shape of the original minerals has in many instances been inherited by their oxidation products.

Oxidation Processes.—A few remarks on the course of the oxidation process in Mount Isa may be of interest:

The oxidation of the pyrite is accompanied by the leaching of carbonates and sphalerite, and the greater part of the sphalerite has disappeared before the formation of the bulk of the hydrous iron oxides begins. It seems that the formation of jasper and iron oxides becomes important only after the greater part of the pyrite has also disappeared. The end product is a fine-grained mixture of jasper and "limonite."

In the German and English literature there is some laxity in the use of terms denoting the various iron oxides. Hematite is Fe_2O_3, and limonite designates a group of hydrated iron oxides. According to Ramdohr-Schneiderhohn: α-Fe_2O_3 is "Nadeleisen-

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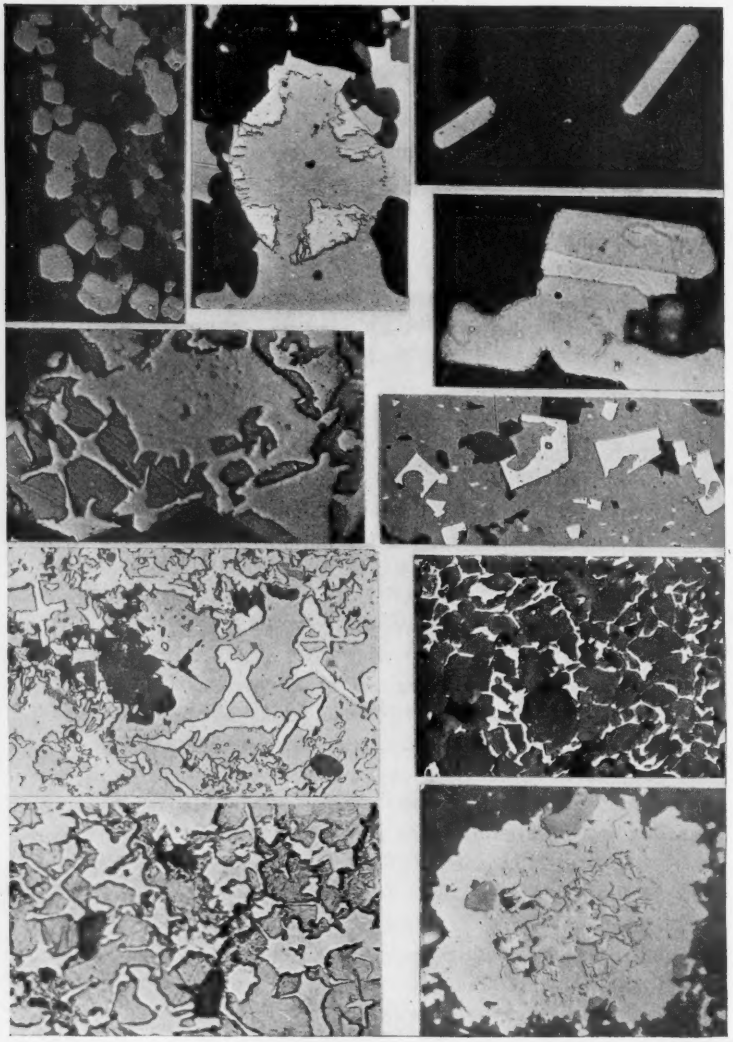


FIGS. 78–87.

erz " or " Samtblende " or " Limonite," and γ-Fe_2O_3 is " Rubinglimmer " or " Lepidokrokit " or " Goethite." Posnjak-Merwin call the α-modification goethite and the γ-modification lepidocrocite. We shall follow here the American classification and consider goethite identical with nadeleisenerz and lepidocrocite with rubinglimmer.

The samples from the pyrite rib and from the roof of No. 1 Panel Footwall Lode, the roof of No. 4 Ore body and from the center of No. 5 Ore body carry abundant goethite. In the roof of No. 5 Ore body lepidocrocite predominates. In all the other samples both hydrous iron oxides occur in varying proportions. The presence of small specks of hematite was suspected in some samples of No. 4 and 5 Ore body, but the fine grains and the strongly colored internal reflexes made determination difficult.

Structures show a wide variety. Microscopically the macroscopic boxwork structure, described by Blanchard and Boswell, occur commonly and also the concentric shell forms with desiccation cracks (Figs. 121, 123). Many pseudomorphs after pyrite are to be found (Figs. 119, 120, 125 and 133). Figs. 122, 124, and 126 show fine boxwork structures in the fine-grained gangue of the lead ores.

FIG. 78. Galena pseudomorphic after irregular pyrite crystals. × 450.

FIG. 79. Last remnants of a pyrite atoll with galena core. × 320.

FIG. 80. Idiomorphic crystals of pyrrhotite in carbonate. × 410.

FIG. 81. Lamella in pyrrhotite (pale gray) selectively replaced by white galena. Carbonate, dark gray. × 450.

FIG. 82. Skeleton-pyrite, partly replaced by galena. × 730.

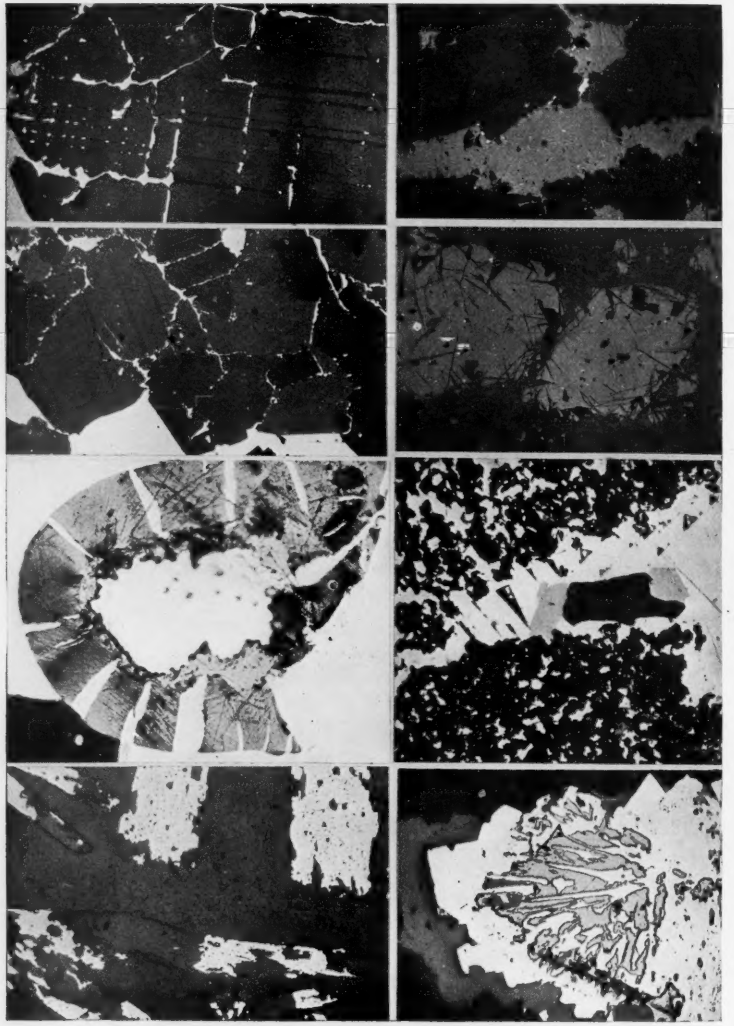
FIG. 83. Idiomorphic pyrite in gray sphalerite, and dark gangue, partly replaced by sphalerite. × 82.

FIG. 84. White pyrite residuals in galena, and gangue. Replacement reveals first skeletons of pyrite growth. Massive pyrite yields etching the same shapes with etching. × 180.

FIG. 85. White pyrite replaces carbonate (high double refraction) from grain boundaries. × 180.

FIG. 86. Originally skeleton shaped pyrite (white) replaced by chalcopyrite (very pale gray). × 730.

FIG. 87. Lens of fine grained pyrite crystals almost replaced by light gray chalcopyrite; outer rims of pyrite left. × 370.



FIGS. 88–95.

The larger cerussite grains enclose well-shaped goethite crystals (Fig. 131) and are in places surrounded by a thin shell of the same mineral.

The spherical pyrite weathers to a mixture of goethite and lepidocrocite, which retains the original shape, or the core may consist of porous lepidocrocite and the shell of goethite (Fig. 129).

The oxidation of ore rich in the more easily oxidizable pyrite variety provides such an abundance of sulphuric acid, that all of the carbonates and the sphalerite are destroyed, and no calamine or smithsonite remain. Where pyrite is scarce, sphalerite resists oxidation better than galena.

A striking fact is that sphalerite, when in contact with pyrite or pyrrhotite, is attacked much more strongly than when in contact with gangue, a natural confirmation of the laboratory evidence of Gottschalk and Buehler.

In the presence of cupriferous solutions, galena and sphalerite are replaced by a mixture of chalcocite and covellite. Galena weathers to anglesite and cerussite with traces of pyromorphite and phosgenite. In the first phase of this process oxidation takes place along cleavage planes and grain boundaries. Fig. 107 shows the form of the replacement in a more advanced stage.

FIG. 88. Replacement of carbonate (dark gray) by galena in places along twinning lamellæ. × 80.

FIG. 89. Normal replacement structure of carbonate by sphalerite. Small specks of chalcopyrite. × 20.

FIG. 90. Galena (white) replaces carbonate (with double refraction) along grain boundaries and twinning lamellæ. × 80.

FIG. 91. Dark gray chlorite laths in sphalerite and carbonated shale on the advancing replacement front. × 36.

FIG. 92. Graphite in various shades of gray (double refraction), radially grouped around pyrite, all in galena, which also fills cracks in graphite. × 400.

FIG. 93. White galena and pale gray polybasite in cross fissures through galena-impregnated gangue. × 36.

FIG. 94. Irregular white pyrrhotite prisms in gray gangue. Prism-shape seems to be due to replacement of certain silicate minerals. × 20.

FIG. 95. Part of pyrite aggregate (white) replaced by galena (very pale gray), starting from the center. × 80.

When the last galena has been oxidized, and, owing to the paucity of pyrite, carbonate gangue has been spared, the determination of the minerals anglesite, cerussite, smithsonite and of the gangue carbonates presents difficulties. The sulphidizing method, developed by the junior author [2] has proven very useful in solving doubtful cases. Fig. 7 and Figs. 134 and 135 illustrate this. Fig. 134 shows a sample before and Fig. 135 after treatment with FNa_2S. The pseudomorphs of artificial galena after pyrite have been produced by sulphidizing of the anglesite, which in its turn had been formed by natural oxidation of an original pseudomorph of galena after pyrite. This method enables a rapid distinction between the carbonates of lead and those of iron, lime and magnesia to be made.

Pseudomorphs of galena after spherical pyrite, may assume curious atoll-shaped forms, to be described in more detail below, owing to preferential replacement of certain layers in the zonally built pyrite crystals. These shapes generally survive the oxidation process: if the core is galena, and the shell pyrite, the core is first transformed into anglesite (Fig. 127). On sulphidizing, the core is remade into galena, the original combination is restored, and the identity of the core established.

Fig. 130 shows a few irregular atoll-shapes after complete oxidation. The cores (originally galena) are now anglesite, the shell and a few grains enclosed in the core (formerly pyrite residuals) are now goethite. Cerussite occurs in the same shapes as anglesite but it is limited to the upper levels.

Pyrrhotite oxidizes readily and shows the first signs of tarnishing and formation of marcasite in the midst of fresh sulphides. Covellite, accompanied by small amounts of chalcocite, is found as rims from 1 to 4 mm. thick, around galena residuals in the oxidized ore: a miniature cementation zone around sulphide nucleii.

In the outcrops the slate is strongly silicified, and colored by iron oxides.

[2] Schouten, C.: Structures and textures of synthetic replacement. ECON. GEOL., vol. 29, pp. 611–658, 1934.

HYPOGENE METASOMATIC REPLACEMENT.

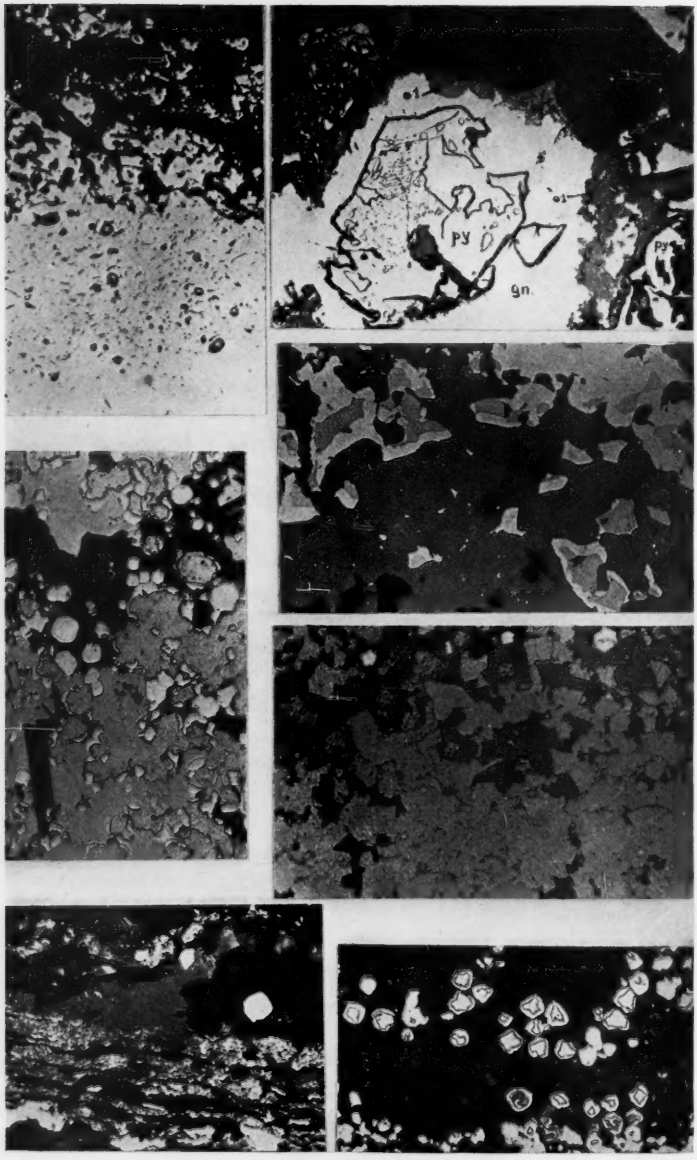
The complex structure of the Mount Isa ore is liable to provide economic geologists with as many solutions of the genetic problem as there are theories, but the two theories that deserve most serious consideration are those of syngenetic deposition and of metasomatic replacement. The authors do not hesitate to declare that they are in favor of metasomatic replacement, because it is most in accord with the observed phenomena. A description of microscopic structures will be necessary to explain their point of view.

Five pyrite varieties have been described, of which three were deposited before crushing and faulting of the country rock. Pyrite being the oldest sulphide, replacement structures of pyrite by younger sulphides will be considered first. In the deeper levels of the Black Star mine, along the No. 6422 coordinate, chalcopyrite, replacing pyrite, predominates among the younger sulphides. All the pyrite varieties retain their original structure wholly or in part, if the replacement has not proceeded so far as to change the whole ore structure. Even then etching often reveals the pyrite structure.

As a rule the outer shells of the pyrite spheres or crystals resist replacement better than the core, with the exception of the skeleton variety. Fig. 87 shows an aggregate of pyrite crystals almost wholly replaced by chalcopyrite. The crystal outlines, spared by replacement, betray the identity of the host mineral. Complete pseudomorphism with inheritance of the pyrite shape by chalcopyrite is common.

Massive blebs of chalcopyrite generally show sufficient pyrite remnants to justify the conclusion that pyrite was the original sulphide (Fig. 72). Fig. 66 shows complete pseudomorphs in marked contrast with Fig. 72. If the chalcopyrite has recrystallized, which is commonly the case, etching of course does not reveal the pyrite structure, but often shell residuals of the pyrite are helpful. Large pyrite crystals commonly suffer zonal replacement by chalcopyrite, visible in all stages.

The replacement of the skeleton pyrite results in entirely dif-



FIGS. 96–102.

ferent structures. All stages are found, from crystal skeletons to full grown pyrite crystals, where the earliest skeleton growth is found as replacement nucleii in the chalcopyrite (Fig. 87).

Galena is much more abundant than chalcopyrite and this accounts in part for the greater variety of structures in the replacement of pyrite by galena. A normal case is shown in Fig. 97. A pyrite crystal has been irregularly corroded and replaced by galena, the crystal outline has offered more resistance than the interior. Very characteristic for Mount Isa is the shape that has already been called "atoll." The purest atoll shapes originate in the irregular spherical pyrite concretions (Figs. 61 and 68). The core may be galena, sphalerite, or both together; the shell is pyrite. This shell may be single or double, closed or open, or broken up into fragments (Fig. 77: irregular atoll with pyrite residuals). The final stage, when the last pyrite residuals have disappeared, is formed by irregularly rounded shapes of galena or sphalerite imbedded in gangue. Fig. 108: atoll with double pyrite rim. Fig. 79: last stage in replacement process, with last remaining

FIG. 96. Replacement of gangue by chalcopyrite. White with high relief pyrite. × 90.

FIG. 97. Pyrite crystal (white) partly replaced by galena. Very dark gray, quartz. Anglesite (dark gray) at contact of quartz and galena. × 50.

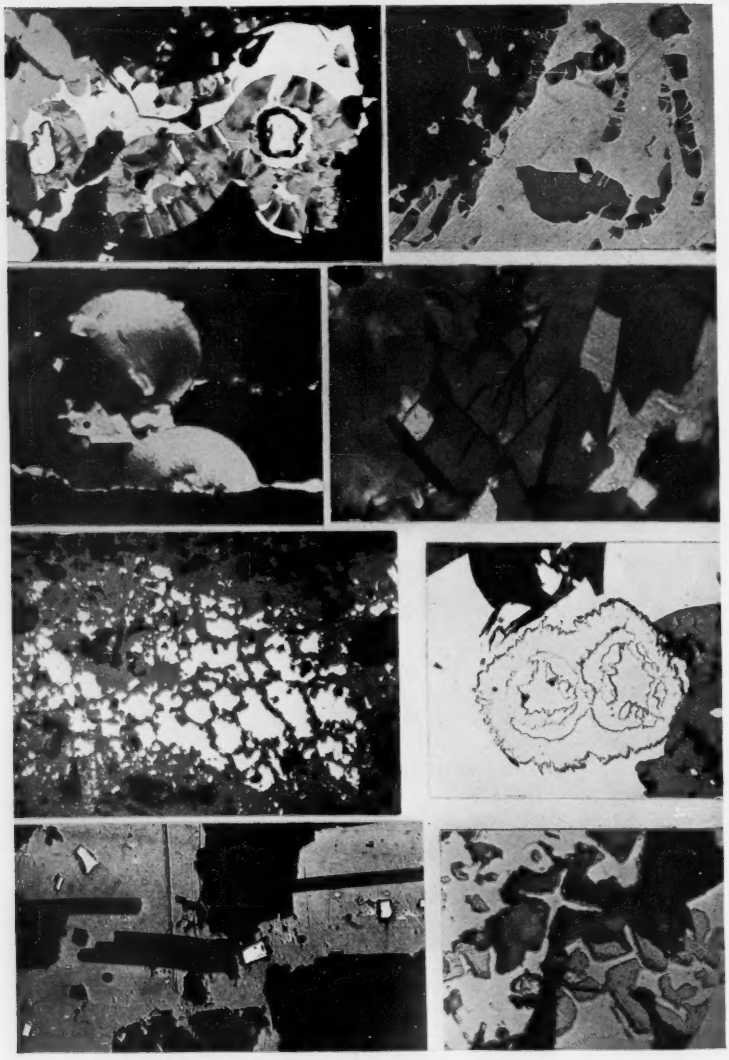
FIG. 98. Pyrite spheres here completely replaced by light gray pyrrhotite. Galena specks, white and round, in the pyrrhotite, outline the original atoll shape. Irregular pyrite residuals with high relief. × 450.

FIG. 99. White chalcopyrite replaces gray pyrrhotite in darker gray sphalerite from their contact. × 110.

FIG. 100. Galena, weakly etched, rough surface, and pyrrhotite grains, pseudomorphic after pyrite. In sphalerite (gray) with very little gangue. Below, some pyrite residuals. × 600.

FIG. 101. Layers of graphite (gray, spotty), carbonaceous matter (dark gray) in black shale. Irregular gray sphalerite bleb. A white galena pseudomorph after pyrite. × 1000.

FIG. 102. Replacement structures of various kinds of pyrite. Left, irregular atolls; right, pyrite aggregate originally with skeleton structure; white with relief, pyrite; very light gray, galena; gray, sphalerite; black, gangue. × 110.



FIGS. 103–110.

pyrite residuals. In places the process is obscured by galena that replaces both pyrite and surrounding sphalerite (Fig. 74).

Replacement of the fine-grained oldest pyrite spheres or crystals gives different structures: Figs. 102 and 69 show a layer of these atolls with clearly visible crystal outlines. Fig. 71: last stage, galena pseudomorphous after pyrite. On comparing Fig. 71 with Fig. 65, pseudomorphous replacement cannot be doubted. It may safely be assumed that irregular shapes, shown in Fig. 78, are due to the same process. This is important, because it would indicate that galena has replaced pyrite, after this mineral, even if it had been deposited as a gel together with the sediments and had recrystallized to idiomorphic crystals, whereas the theory of syngenetic deposition postulates that sulphides were originally deposited as mixed gels, to crystallize afterwards.

In the spherical pyrite the different stages of the process can be followed by looking at Fig. 73: galena and sphalerite pseudomorphs after pyrite spheres, and crystals. Fig. 70 shows the last stage of replacement of an aggregate of pyrite spheres. The original limit of the pyrite spheres is generally marked by a narrow rim of undigested impurities, pushed to the circumference,

FIG. 103. Dark gray carbonate, gray sphalerite, white (high relief) pyrite, white galena, light gray tetrahedrite; gray in various shades around pyrite is graphite with strong double refraction. Galena on grain boundaries between pyrite and graphite and filling fissures in graphite. × 380.

FIG. 104. Gray graphite in galena and carbonate. Parallel nicols. Shattered graphite rings. × 95.

FIG. 105. Curious graphite shapes in dark carbonate. White, galena. × 1900.

FIG. 106. Dark gray, sphalerite; very dark gray, chloride laths; pale gray, galena, on the advancing replacement front. × 950.

FIG. 107. Last remnants of galena (white) in anglesite (gray) and dark quartz. Replacement started from grain boundaries. × 140.

FIG. 108. Double atolls with double rims. White (with relief) is pyrite; white, smooth is galena; gray, sphalerite. × 190.

FIG. 109. Gray sphalerite replaces dark gray carbonate, guided by twinning structure. White pyrite grains. × 190.

FIG. 110. Skeleton pyrite in black gangue (internal reflexion) and white galena. × 950.

and which generally consist of graphite and carbonaceous matter. Replacement of pyrite aggregates and skeleton pyrite results in the same structures, as shown in Figs. 84 and 86.

In addition to the atoll shapes of pyrite and galena other combinations are found. The core may be filled with sphalerite, pyrrhotite or galena or a mixture of these. On etching, galena commonly shows the shadow structure of the original concentric shells. Normal replacement structures are also common; cracks in pyrite filled with galena, or pyrite grains are irregularly replaced by it.

Structures of pyrite with pyrrhotite or sphalerite as metasome are not so convincing as those described. Fig. 83 shows partial replacement of large idiomorphic pyrite crystals by sphalerite, Fig. 50 residuals of early pyrite layers in sphalerite. Two stages of atoll building are given in Figs. 75 and 64.

Fig. 100: pyrrhotite pseudomorphs after pyrite crystals. Tetrahedrite occurs in the same way.

Pyrrhotite that has replaced pyrite commonly has a spotty appearance and encloses galena with pyrite outlines.

The structures described establish without doubt that pyrite is older than the other sulphides and has been replaced by them. The relations between the sulphides and the gangue minerals are important for genetic reasons. Both the original carbonate in the slate and the later hydrothermal carbonate are older than the younger sulphides. Replacement of carbonate by sulphides presents varied features—carbonates are veined with sulphide-filled fissures, without matching walls irregularly wide and narrow, or sulphides penetrate the carbonate along crystallographic directions. Fig. 52 shows the influence of crystal structure of the carbonate on the shape of chalcopyrite.

Fig. 35 provides another strong argument for metasomatism; a close relation exists between the grain size of the carbonate and that of the sulphides. In coarse-grained carbonate, chalcopyrite also is coarse. If quartz grains are imbedded in the carbonate, they are free from sulphides (Fig. 49). Even more convincing are the replacement structures of the fine-grained carbonate that impregnates slate. The fine carbonate may be host

mineral to galena, chalcopyrite, pyrrhotite and tetrahedrite, these sulphides following grain boundaries and crystallographic planes (Figs. 39, 88, 90, 91). Fig. 41 shows how the rhombohedral planes resist replacement better than the interior of the carbonate.

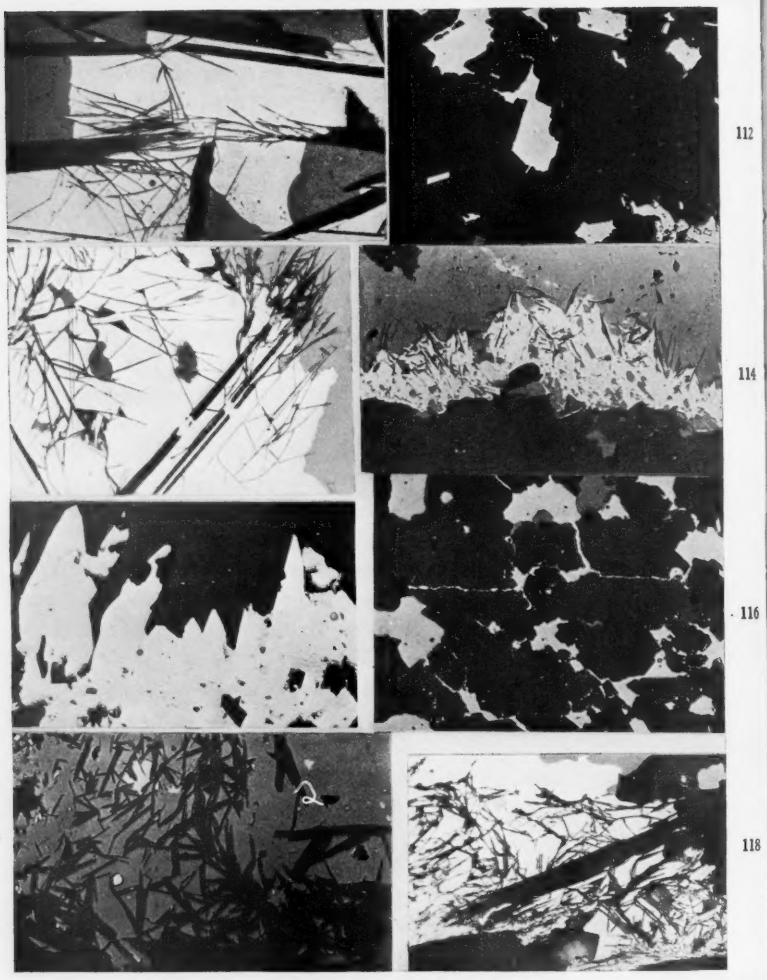
Fig. 44 shows tetrahedrite and chalcopyrite in similar structures. Replacement of carbonate by pyrrhotite and sphalerite, possibly due to higher temperature, is more sweeping, and does not follow the structure so closely; an exception is shown in Fig. 89. Fig. 109 shows preferential attack of carbonate twins by sphalerite; the same for pyrrhotite is illustrated in Figs. 112 and 116.

Relations between slate and the sulphides are complex; the mineralization has either resulted in total disappearance of the slate, or only fissures have been filled. These two forms pass into each other by innumerable transitions, in which the fissure walls are progressively attacked by the mineralizing solutions. Commonly fissure mineralization where it abuts a bedding plane, broadens into complete mineralization of a slate band. Figs. 26, 30, 31 and 37 show these structures.

In places lens-shaped slate particles have either been replaced more easily or have offered more resistance to the solutions than the surrounding material (Fig. 45). Fig. 43 shows clearly how different the resulting structure of a fine-grained slate is from that of a coarse quartz-carbonate intergrowth. Fig. 32 illustrates the different shapes that galena and sphalerite derive from replacement of the same slate. Sphalerite is accompanied by newly formed silicate laths. Fig. 55 shows that pyrrhotite replaces slate without affecting older pyrite; this is also true for arsenopyrite (Fig. 59).

In a sample from the Black Rock mine a fairly large mass of penninite was found. Figs. 54 and 55 show replacement structure along its border. Fig. 81 shows that lamellæ in pyrrhotite grains are transformed into galena.

The silicate crystals, which commonly accompany sphalerite, have not been bent or broken in spite of their dimensions (0.01 by 0.002 mm.) and they must have been formed after the period of



FIGS. 111–118.

crushing and faulting (Figs. 29 and 113). When in its turn sphalerite is replaced by galena, these prisms frazzle out into numerous extremely fine needles (Figs. 111, 113, 117, 118, 114).

The authors believe that the structures described can be explained only by attributing the mineralization to metasomatism.

GENESIS OF THE ORE.

The mineralization in the Black Star mine can be divided into three periods:

1. Formation of the slates with a certain amount of carbonate, and possibly with the simultaneous deposition of part of the pyrite. Another more plausible assumption is that this pyrite was deposited by replacement as a forerunner of the later economic mineralization.
2. Crushing and faulting of the pyritic slates and deposition of sulphides of iron, zinc, copper and lead.
3. Supergene oxidation processes.

In the second period the mineral sequence is: arsenopyrite,

FIG. 111. Dark gray chlorite laths with sphalerite and galena. In galena the laths are fuzzy. × 240.

FIG. 112. Pyrrhotite in dark carbonate with twin lamellæ. Boundaries of pyrrhotite crystals defined by cleavage planes (upper left) and twinning structure. × 86.

FIG. 113. Chlorite laths, dark gray, in white galena and light gray sphalerite. Notice how galena eats its way through one of those laths without disturbing it. × 380.

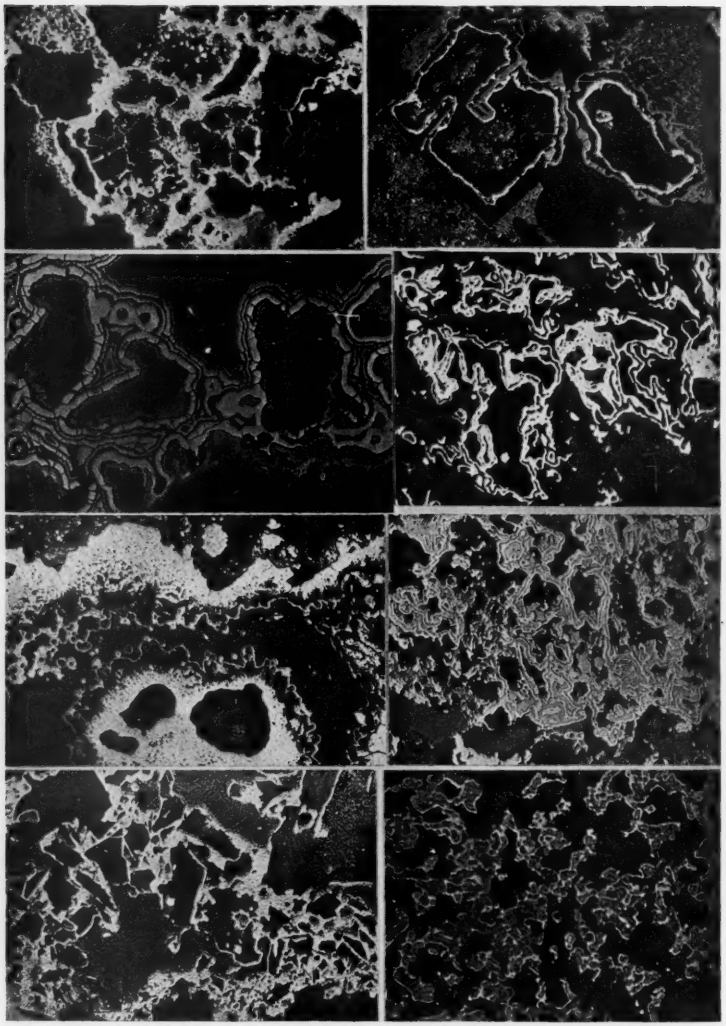
FIG. 114. Light gray galena replaces gray sphalerite at its contact with penninite (dark gray). In sphalerite and galena are residuals of chlorite laths. × 86.

FIG. 115. Crystal terminals of unknown mineral in gangue. × 190.

FIG. 116. Pyrrhotite in dark carbonate; its shape is defined by twinning and cleavage of carbonate. × 86.

FIG. 117. Chlorite laths in gray sphalerite. White, pyrite and galena. × 86.

FIG. 118. Chlorite laths (dark gray) strongly bent in galena; sphalerite, light gray. × 380.



FIGS. 119–126.

pyrite, graphite, quartz, carbonate, white unknown mineral, sphalerite, pyrrhotite, tetrahedrite, chalcopyrite, marcasite, galena.

The sequence in the supergene zone is: chalcocite, covellite, anglesite, cerussite, jasper, goethite, lepidocrocite.

It is hardly necessary to affirm that this sequence is valid only in a general way, and that overlapping and recurrence of mineralizations occur.

The assertion that the pyrite mineralization may be syngenetic with the deposition of the slates, is more a reluctant admission that it has been impossible to prove the contrary by microscopic study, than an expression of the author's opinion. To an American or English geologist it may seem superfluous to discuss the theory of syngenetic pyrite deposition, but an influential European school of economic geologists still advocates for certain ore deposits the syngenetic deposition of a mixed mineral gel on sea or lake bottoms. We believe that the theory of the more or less simultaneous deposition of mineral gels has been exploded as far as the later sulphides are concerned. We admit that we have not been able to prove by our microscopic study the metasomatic replacement of the slate by the older pyrite, but a written communication from the staff of the mine reads as follows:

FIG. 119. White lepidocrocite replaces dark jasper. ×75.

FIG. 120. Surface. Concentric structure of goethite and lepidocrocite in jasper. Original pyrite shapes still discernible. × 75.

FIG. 121. Surface. Very fine shells of lepidocrocite (and hematite?). Atoll shapes are due to gel precipitation. × 75.

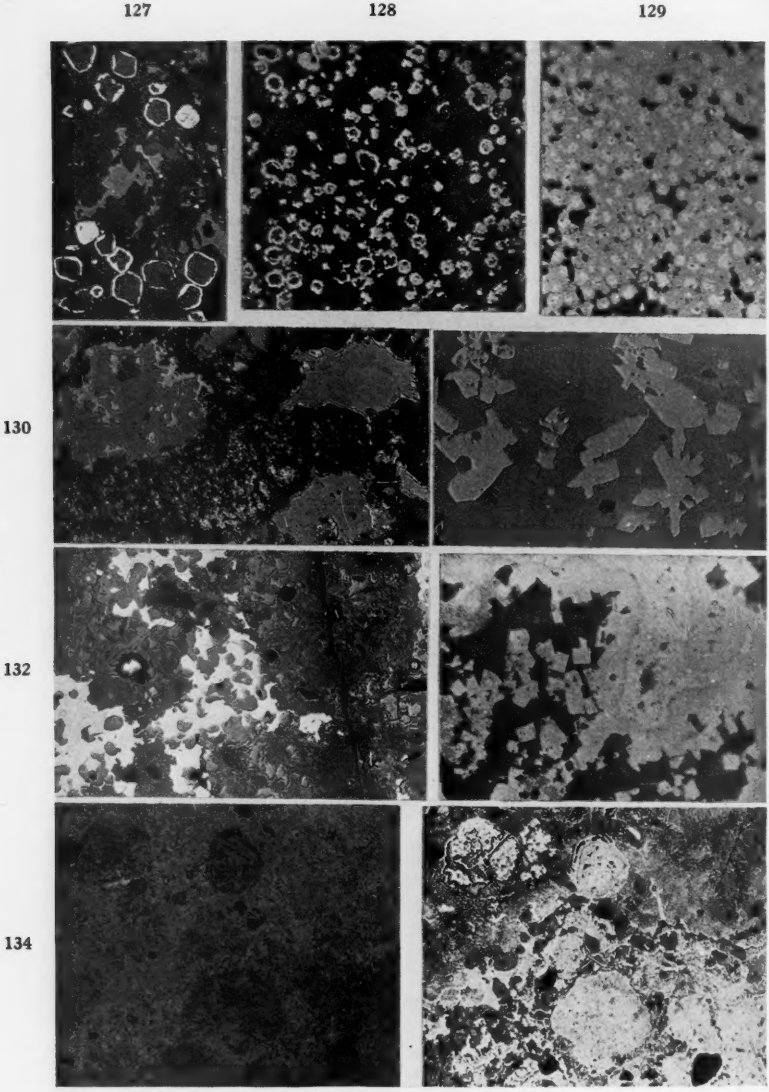
FIG. 122. Surface. Fine boxwork structure, lepidocrocite in jasper, × 200.

FIG. 123. Surface. Concentric layered goethite (dark gray) and lepidocrocite (light gray) in very dark jasper. Atoll shapes not due to inherited structure but to gel precipitation. × 42.

FIG. 124. Fine boxwork structure of goethite and lepidocrocite in jasper. Surrounded by oxidized lead ore. × 165.

FIG. 125. Surface. "Limonite," light gray, on grain boundaries of dark quartz. Dark gray and rough surface, shellac of preparation. × 165.

FIG. 126. Fine boxwork structure of goethite and lepidocrocite in jasper, surrounded by oxidized lead ore. × 420.



FIGS. 127–135.

As to pyrite mineralization extending beyond limits of the ore, we may state that the oreshoots occur where shearing is most strongly developed and that shearing coincides closely, though not absolutely, with the strike and dip of the shale beds. Where shearing of a weaker nature along the bedding planes persists beyond the ore limits, pyrite mineralization likewise persists (in some instances up to a mile or more beyond limits of the ore laterally, and at least several hundred feet in depth below lead and zinc sulphides) and when shearing fails to persist along the beds that usually carry ore, the beds as a rule are wholly barren of mineralization in any form.

This field evidence supplements our laboratory work, and seems to prove without doubt that the heavy pyritization in Mount Isa is best explained, not by syngenetic deposition near the surface, but by the assumption that the same mineralizing agents and the same

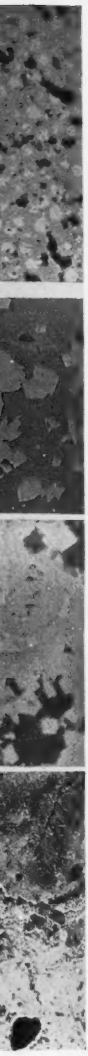


FIG. 127. Incompletely oxidized ore. Pyrite, white; sphalerite, light gray; dark gray, anglesite; very dark gray, gangue. Atolls of anglesite core and pyrite rim resulted from oxidation of pyrite-galena atolls. × 350.

FIG. 128. Spherical pyrite transformed into lepidocrocite (white), in black jasper. Core is softer and more easily polished away: false atoll shapes. × 435.

FIG. 129. Surface. Goethite (gray) with lepidocrocite and hematite cores (light gray) in black jasper. The iron oxides are pseudomorphic after pyrite spheres. Even here difference between rim and core has been preserved. ×435.

FIG. 130. Surface. Dark gray anglesite surrounded by rims of goethite (light gray) in a ground mass of jasper (very dark gray). Influence on flotation of anglesite. × 87.

FIG. 131. Surface. Goethite crystals (light gray) in dark gray cerussite. ×180.

FIG. 132. Galena and sphalerite replaced from a crack by covellite and anglesite. White grains with high relief are pyrite, dark gray quartz. Oxidation starts from the crack and from the original grain boundaries. × 44.

FIG. 133. Surface. Goethite and lepidocrocite partly pseudomorphic after pyrite, partly built up concentrically. × 350.

FIG. 134. Oxidized ore with anglesite, covellite, quartz, carbonate and limonite. × 87.

FIG. 135. Same as Fig. 134. Oxidized ore after sulphidizing. Anglesite changed to galena. Right and left limonite rims around the synthetic galena are visible. ×100.

structural features of the district (shearing, faulting, crushing) were responsible for both the older pyrite and the younger sulphides, with the limitations imposed by zonal arrangement and lag in period of deposition.

The first period of mineralization should then read: "Shearing of the slates and early mineralization by pyrite through replacement."

ACKNOWLEDGMENTS

Many thanks are due to the London directors and to the staff of Mount Isa Mines Ltd. for their willingness to supply us with a large suite of carefully taken samples and for their authorizing this publication.

TECHNISCHE HOOGESCHOOL,
DELFT, HOLLAND.
Mar. 5, 1937.

RECENT GEOLOGIC STUDIES ON LONG ISLAND WITH RESPECT TO GROUND-WATER SUPPLIES.[1]

DAVID G. THOMPSON, FRANCIS G. WELLS, AND HORACE R. BLANK.

ABSTRACT.

Recent studies have shown that relatively impermeable clay beds are widespread on Long Island but that erosion channels cutting through them permit restricted recharge of the underlying beds in some parts of the island. Of the more than 200,000,000 gallons of water a day now pumped from wells, about 65 per cent. comes from the surficial beds of Illinoian or Wisconsin age. Because of the restricted recharge of the lower beds and the desirability of saving these beds for use in localities where the upper beds may more easily be contaminated by salt water, any future large developments of ground water should be drawn from the surficial beds.

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INTRODUCTION.

THE ground-water resources of Long Island are among the most productive and most highly developed in the United States. In

[1] Read at joint meeting of Geological Society of America and Society of Economic Geologists in New York, December 27, 1935. Published by permission of the Director of the U. S. Geological Survey.

some years 260,000,000 gallons of water a day have been pumped from wells for public supply and private use in the boroughs of Brooklyn and Queens and Nassau County. The greater part of this water has been used in that part of the city of New York lying within the two boroughs mentioned. Although only a relatively small quantity of water has been developed in Suffolk County, there is opportunity for additional large development there.

Many extensive investigations of the potential water supplies of the island, both surface water and ground water,[2] have been made. So far as the geologic conditions are concerned the principal studies have been those of W. O. Crosby,[3] which continued over many years for the city of New York but which are largely unpublished; and those of A. C. Veatch, M. L. Fuller, and others, for the United States Geological Survey.[4] Since 1932, the United States Geological Survey, in cooperation with the State of New York and Nassau and Suffolk Counties, has made further geologic and hydrologic studies.

Although agreeing as to the broad features of stratigraphy, Crosby, on the one hand, and Veatch and Fuller on the other, have held divergent opinions in regard to certain fundamental interpretations of the stratigraphy and structure of Long Island. It has therefore become necessary for the present investigators to reconcile the ideas of these two groups or to make new interpretations on the basis of new evidence. In this brief paper it is pos-

[2] See especially Report of the Commission on Additional Water Supply for the city of New York, Martin B. Brown Co., 1904; Long Island sources, an additional water supply for the city of New York, 2 vols., City of New York, Board of Water Supply, 1912.

[3] Crosby, W. O.: Outline of the geology of Long Island in its relation to the public water supplies, in Freeman, J. R.: Report upon New York's water supply, appendix 16, pp. 553–572, Martin E. Brown Co., 1900. Much of this report under the same title was published in Tech. Quart., vol. 13, 100–119, 1900. Also an unpublished report submitted to the City of New York Board of Water Supply under date of November 12, 1910 (64 typewritten pages), and a subsequent uncompleted report in the possession of his son, Irving Crosby.

[4] Veatch, A. C., and others: Underground water resources of Long Island. U. S. Geol. Surv. Prof. Paper 44, 1906. Fuller, M. L.: The geology of Long Island, N. Y. U. S. Geol. Surv. Prof. Paper 82, 1914. See also several short papers referred to in Fuller's report.

sible to state only a few of the most significant facts developed by the present investigation. In a study of the ground-water supplies of Long Island the geologist is primarily interested, first, in the extent and relative permeability of potential water-bearing formations, and second, in the presence or absence of relatively impervious clay beds that may restrict downward movement of water to recharge the lower beds or, along the coast, may serve to prevent salt water from entering the water-bearing beds; but studies of these apparently simple factors have led rather far afield into problems that may at first seem to be more of an academic than a practical nature.

GEOLOGIC CONDITIONS AFFECTING THE OCCURRENCE OF GROUND WATER.

Cretaceous Formations.

As would be expected, on Long Island ground water in abundance occurs only in the unconsolidated sediments of the Coastal Plain. The lowermost of these formations consists of a considerable thickness of beds of Cretaceous age, which strike approximately east-northeast and dip south-southeast. (Figs. 1 and 2.) These underlie practically the entire island except at its west end, where they have been removed by erosion. The Cretaceous beds lie unconformably upon the ancient bedrock, or its decayed equivalent, the surface of which has a local relief of a magnitude of 100 feet. From observations in shafts for water tunnels and studies of drill cuttings there is reason to believe that considerable thicknesses of clay just above the bedrock, formerly considered to be of Cretaceous age, are really a thick lateritic mantle of the decayed bedrock.

The lower part of the Cretaceous, believed to be mostly of Raritan age, consists largely of clay except for a single water-bearing zone which Veatch called the "Lloyd sand." The recent studies suggest that the Lloyd may consist of three separate beds, but in some places at least one of these beds and in other places all three have been removed by erosion. Or, alternately, the lower bed may not have been deposited on a high point in the

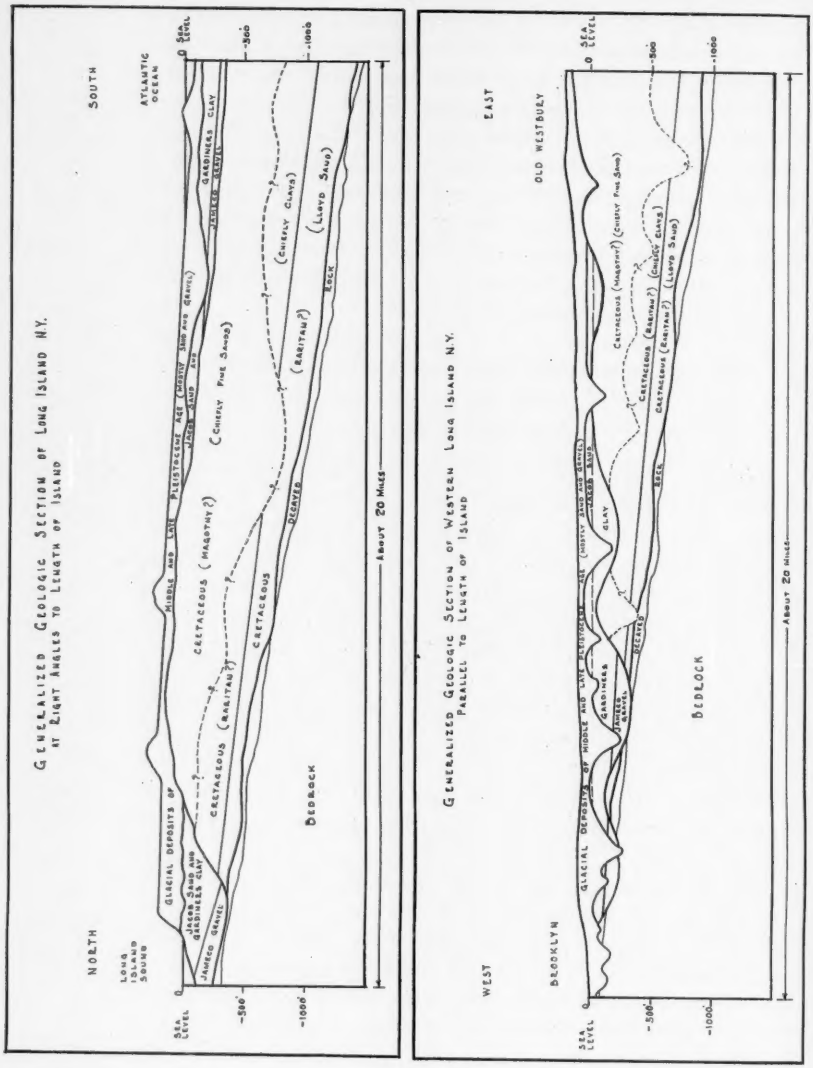

FIG. 1: (upper). Generalized cross section from north to south in the vicinity of Jamaica, Long Island.
FIG. 2. (lower). Generalized cross section from southwest to northeast between Brooklyn and Old Westbury.

underlying bedrock surface. The upper part of the Cretaceous beds, believed to be mostly of Magothy age, consists largely of sand. Much of the sand is too fine to yield water to wells, but in recent years several wells have been completed at certain horizons that are believed to be in the lower part of the beds of Magothy age.

Veatch considered the clay beds to be discontinuous lenses, which although retarding downward movement of water to the lower beds did not greatly reduce recharge.[5] However, the logs of many wells show that in the lower part of the Cretaceous section the clay beds are so widespread and so thick that it seems more likely that they originally covered the entire area and that the absence of the clay in some wells is due to erosion rather than to original lenslike deposition. In fact, W. O. Crosby considered the clay above the Lloyd sand to be so continuous that recharge would be impossible except in the west end of the island, where the clay had been removed.[6] This interpretation—that is, entire absence of recharge of the Lloyd sand over most of the island—does not seem correct, for the simple reason that the hydrostatic head on water in the sand is highest, not in the only area where Crosby believed recharge was possible, but in the central part of the island some miles farther east, and this necessarily implies recharge there. Detailed studies by H. R. Blank during the past year suggest that the unconformity between the Raritan and Magothy is greater than was originally believed and that in places erosion has cut completely through the thick clay beds into the Lloyd sand and in at least one place removed that sand. If there is an unconformity of sufficient magnitude to cut into the Lloyd sand, recharge of that sand elsewhere than in the west end of the island is possible, although doubtless confined to small and scattered areas. The magnitude of this apparent unconformity, however, is so much greater than the known magnitude of the unconformity between the same formations in New Jersey that final

FIG. 1. (upper). Generalized cross section from north to south in the vicinity of Jamaica, Long Island.
FIG. 2. (lower). Generalized cross section from southwest to northeast between Brooklyn and Old Westbury.

[5] Veatch, A. C.: *Op. cit.*, p. 55 and Fig. 24.

[6] Crosby, W. O.: Unpublished report for City of New York Board of Water Supply.

FIG. 3. Map of western part of Long Island showing contours on the post-Cretaceous, pre-Pleistocene erosion surface.

judgment must be reserved until more conclusive evidence is obtained.

In post-Cretaceous time the Cretaceous beds were greatly eroded, so that their present surface is highly irregular. A map prepared by F. G. Wells shows this post-Cretaceous, pre-Pleistocene surface for the west half of the island. (Fig. 3.) It shows principally the top of the Cretaceous beds except in the extreme western part of the island, where those beds have been removed; there the bedrock surface is represented. Although this map may be modified as more detailed information becomes available, it undoubtedly shows correctly certain significant facts. The post-Cretaceous island had much the same form as the present island, but the portion above present sea level was much smaller. The north shore of the island was indented by steep-sided valleys, mostly beneath the present-day valleys but deeper and extending somewhat farther inland. Although not shown on the map, there is some indication of several outliers or islands on the site of present-day headlands, such as Lloyds Neck and Eatons Neck, separated from the main body by an elongated valley. The valleys on the south side of the island were not as deep as those on the north side, but they were considerably wider and deeper than the present south-side valleys.

Particularly significant are the relief features of the post-Cretaceous surface near the west end of Long Island. Veatch[7] postulated a large valley, which he called the "Sound River Valley," extending northward across the island from the vicinity of Jamaica Bay to Long Island Sound. Crosby also recognized a Sound River Valley, but he considered it to be somewhat farther west than the position postulated by Veatch.[8] If the comparatively few and inadequate logs of wells in this locality have been correctly interpreted, as shown by the recently prepared map, there are really two major valleys instead of one.

[7] Veatch, A. C.: *Op. cit.*, p. 34.

[8] Crosby's interpretation is revealed by cross sections accompanying his unpublished report for the City of New York Board of Water Supply.

FIG. 3. Map of western part of Long Island showing contours on the post-Cretaceous, pre-Pleistocene erosion surface.

Pleistocene Formations.

Early Pleistocene Deposits.—Tertiary deposits appear to be absent over most of Long Island but may be present in small areas at its east end. Except for these beds the next formation above the Cretaceous is the Mannetto gravel, considered by Veatch and Fuller to be early Pleistocene but by Crosby to be Tertiary. The most distinctive characteristic of this gravel, according to Fuller's description, appears to be the presence of sparsely distributed badly weathered and disintegrated granitic pebbles and crystalline boulders. As these features are difficult to distinguish in drill cuttings, it has been impossible to recognize this gravel definitely in wells, and doubtless it has been unknowingly correlated with either higher or lower formations.

Jameco Gravel, Gardiners Clay, and Jacob Sand.—Next above the Mannetto is the Jameco gravel. The distinctive characteristic of this gravel is its heterogeneous content of crystalline pebbles and cobbles that are obviously erratics. Veatch interpreted the Jameco gravel to represent the outwash from a glacier which, as no till from it has ever been found on Long Island, probably never moved south of Long Island Sound; but the debris from this glacier washed into the valleys on the north shore, the Sound River Valley at the west end of Long Island, around the east end of the island, and possibly through other deep valleys if any cut entirely across it. The type locality of the Jameco, where it is well developed, is in the Jameco well field of the City of New York Water Department, in the southern part of the Sound River Valley as originally located by Veatch, but it is also well developed in the other major valley farther west. Recognizable Jameco beds have not been found on the south side of the central part of the island—a fact which is in agreement with Veatch's interpretation, for the high mass of the island would act as a barrier to prevent direct southward movement of the outwash from the Jameco glacier, which could move only around the ends of the island. The Jameco gravel is in general abundantly water-bearing, but resting as it does on an irregular surface, in places it fills only small pockets that are surrounded by less permeable clay and do not yield much water.

Above the Jameco gravel is the Gardiners clay, which grades upward conformably through silt into the Jacob sand. These beds are distributed around the borders of Long Island and in the Sound River valley, and they were presumably deposited during an interval between stages of glaciation, being tentatively assigned by Fuller to the Yarmouth interglacial stage. The Gardiners clay plays an important part in the occurrence of ground water, for two reasons—first, it acts as an impervious cover under which the water is under artesian pressure, and recharge can take place only at its landward edge, or through erosion channels cut through it; second, it prevents salt water from reaching the fresh-water beds beneath it.

Crosby questioned the glacial origin of the Jameco gravel. He considered it to be the same as a gravel—to which he applied the name "Bethpage gravel"—which he found in the pits at Bethpage, on the south side of the high Cretaceous hills in the middle of the island, and which he believed to be of Miocene age.[9] The overlying clay, presumably the equivalent of the Gardiners of Fuller, he correlated with the Kirkwood (Miocene) of New Jersey. This would make the Bethpage gravel of Crosby, and accordingly also the Jameco, apparently the equivalent of the well-recognized 800-foot water-bearing sand at Atlantic City. Furthermore, he considered that both the Miocene clay and his underlying Bethpage gravel underlay almost the entire island as continuous bodies.[10] If this were true his Bethpage gravel would constitute a widespread water-bearing gravel, but the clay would act as a blanket to prevent downward movement of water to recharge it.

[9] This and the following statement are based principally upon the fact that, in a number of well logs which accompanied his report to the Board of Water Supply and which he re-correlated, Crosby designated as "Bethpage" and "Kirkwood," respectively, beds that Veatch in Professional Paper 44, correlated as Jameco and Sankaty (which Fuller called Gardiners). Some of these wells were in the type locality of the Jameco gravel. See also, Berkey, C. P.: Geology of the New York City (Catskill) aqueduct. New York State Mus. Bull. 489, p. 36, 1911; and Berkey, C. P., and Sanborn, J. F.: Engineering geology of the Catskill water supply. Am. Soc. Civil Eng. Trans., vol. 86, pl. 3 (opp. p. 66), and discussion by Walter E. Spear, p. 24, 1923.

[10] See cross section and map, Figs. 17–B and 17–C, pp. 114 and 560, of Crosby's appendix 16 in report by John R. Freeman, cited above.

The present investigators are unable to agree with Crosby's interpretation. They believe that there can be no reasonable doubt as to the glacial origin of the Jameco gravel as found in many wells over a large area, and the observed facts fit closely with explanations given by Veatch and Fuller of the origin and distribution of the Jameco and Gardiners. Certainly Crosby's correlation of the Jameco gravel and Gardiners clay in the vicinity of Jamaica Bay with the gravel and the Kirkwood clay in the Bethpage pits is erroneous; and if his assignment of the beds in the Bethpage location to the Miocene is correct these beds can represent only an outlier of comparatively small extent.

Illinoian or Wisconsin Deposits.—The uppermost beds on Long Island consist largely of a considerable thickness of sand and gravel deposited as glacial outwash, in places interspersed with relatively thin beds of till. Fuller considered these beds to be in part of Illinoian age (the Manhasset formation, which he divided into the Herod gravel, the Montauk till, and the Hempstead gravel) and in part of Wisconsin age. Crosby early expressed the belief that these deposits were all of Wisconsin age and this belief, with field evidence, was reiterated by F. G. Wells [11] in a paper prepared for the meeting of the Geological Society of America in 1934 and by W. L. S. Fleming [12] in a paper published more recently. There seems to be no question that the several units described by Fuller can be recognized in many places on Long Island, but the evidence as to their age is not so clear. One striking fact opposing Fuller's separation of the beds into two glacial stages is the freshness of the pebbles and boulders in all parts of the section from the base of the supposed Illinoian upward.

Fuller's recognition of Illinoian deposits appears to be based largely on his interpretation of an erosion interval of considerable magnitude, which he called the "Vineyard interval." During earlier work for the City of New York Board of Water Supply,

11 Wells, F. G.: Reconsideration of the Pleistocene geology of Long Island (abstract). Geol. Soc. Am. Proc., 1934, pp. 121–122, 1935.

12 Fleming, W. L. S.: Glacial geology of central Long Island. Am. Jour. Sci., 5th ser., vol. 30, pp. 216–238, 1935.

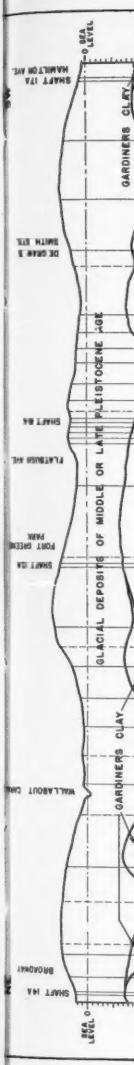

FIG. 4 (upper). Cross section of overburden along part of line of New York City water tunnel No. 2 in Brooklyn. (Based on records of shafts and test borings furnished by City of New York Board of Water Supply.)

FIG. 5 (lower). Graphs showing fluctuations of water level in typical shallow wells in Nassau County 1903–1935. (Based largely on data furnished by City of New York, Department of Water Supply, Gas, and Electricity.)

Blank obtained evidence bearing on this problem. In shafts for a large water-supply tunnel in the western part of Brooklyn and Queens he had the unusual opportunity of seeing some features not revealed in outcrop, including the Jameco gravel, which so far as known, with the possible exception of certain exposures discovered recently, has not been found at the surface anywhere on Long Island and previously had been known only from well cuttings. These shaft studies, with related studies of numerous test borings, have shown erosion channels cut entirely through the Gardiners clay (Fig. 4); and in one shaft Blank saw three separate and distinct tills. The evidence does not show whether this erosion intervel was post-Illinoian, to be correlated with Fuller's Vineyard interval, or whether there were two post-Gardiners erosion intervals—namely, the Vineyard of Fuller and an earlier one. The present evidence permits only the definite dating of this erosion interval as being post-Gardiners.

The Illinoian or Wisconsin deposits are abundantly water-bearing wherever they lie below the water table, except that locally the somewhat consolidated Montauk till may retard downward movement of water to the lower beds. Regardless of age, so far as the occurrence of ground-water is concerned they act largely as a unit, and for the present investigation they have been considered together as glacial deposits of Wisconsin or Illinoian age, or more generally of late or middle Pleistocene age, without definitely dating the lower part of the unit.

Summary of Geologic Conditions

The following facts will briefly summarize the more significant relations between the geology and the occurrence of ground water on Long Island. There are four more or less well-recognized water-bearing zones—first and most productive, the widespread glacial outwash beds of Wisconsin or Illinoian age, which throughout most of the island are not overlain by an impervious cover; second, the Jameco gravel, of somewhat scanty distribution around the northern, western, and probably eastern borders of the island, generally covered by the Gardiners clay; third, in some

localities at least, but not yet proved to be widespread, a fairly good water-bearing zone in the lower part of the beds of supposed Magothy age; fourth, the Lloyd sand, which apparently is covered by clay over large areas. Direct downward recharge to the beds of the third zone is prevented by the Gardiners clay where it is present and probably by clay lenses in the higher Cretaceous beds, but apparently the clay beds are not continuous, and recharge is possible locally in the middle part of the island.

In the western part of the island there is evidence of erosional unconformities cutting through the principal confining clay beds —a post-Raritan, pre-Magothy unconformity indicating erosion that apparently has not only cut deeply into the clay overlying the Lloyd sand but in one or more places has also completely removed the sand; a post-Cretaceous, pre-Pleistocene unconformity of considerable vertical and horizontal extent; and a post-Gardiners unconformity. (See especially Fig. 2.) Although the evidence of these unconformities has so far been developed only in the western part of the island, it seems reasonable to believe that similar conditions exist farther east. One result of these unconformities is that in different places a given formation may rest not merely upon the next older formation but upon any one of the still older formations down to the pre-Cretaceous bedrock. In view of the almost complete absence of fossils and the considerable similarity of lithologic characteristics, this condition complicates the problems of correlation and prediction of the depth to or absence of water-bearing beds. Another result is that there is opportunity for the recharge of the lower water-bearing beds by movement through the erosion valleys—a favorable factor in itself, but, at least so far as the Lloyd sand is concerned, this recharge must be very slight. Also the hydrostatic head on the water in a given bed may be affected by changes in hydrologic conditions, particularly those due to pumping, in the beds that lie either above or below it. Finally, in localities near the coast the beds that contain fresh water may be contaminated by salt water moving in from the sea. In brief, it seems likely that certain irregularities in the distribution of chloride and of water level in the deep and shallow

beds in the western part of the island, hitherto not clearly understood, may perhaps be explained by the interconnection between the beds through erosion channels. However, the details of these interconnections have not yet been worked out.

DISTRIBUTION OF PUMPAGE FROM WELLS ACCORDING TO GEOLOGIC AGE OF SOURCE FORMATION

In 1931, the year of highest pumpage since 1916, the total estimated pumpage from wells in the Boroughs of Brooklyn and Queens and Nassau County, including that from private wells, was about 240,000,000 gallons a day. Reliable statistics, however, are available only for the pumpage from public supplies, which was about 185,000,000 gallons a day. These figures show that the upper glacial deposits have long been and promise to be in the future the chief source of ground water on Long Island, in part probably because they are most productive, and in part because they are the most easily developed. In 1931 these beds furnished 118,000,000 gallons a day, the Jameco gravel 29,000,000 gallons, and the Cretaceous beds 38,000,000 gallons. Although not separately tabulated, the pumpage from the Lloyd's sand does not seem to be as great as might be supposed from the prominence given to this formation in past years.

The relation between geologic distribution of the water-bearing formations and the development for public supply is well brought out by a map (Fig. 6) on which average daily pumpage in 1930 is shown by circles, whose area is proportional to the amount of pumpage, the source formation being indicated by different symbols.[13] If this map is studied closely it will be found, first, that pumpage from the upper glacial beds of Illinoian or Wisconsin age is distributed widely over the entire area; second, that pumpage from the Jameco gravel is confined to areas along the north shore and the two large valleys—the Sound River Valley areas of Veatch and Crosby, respectively, at the west end of the island

[13] For a more detailed statement of pumpage from the different source formations, with fluctuations from year to year, see Thompson, David G., and Leggette, R. M.: Withdrawal of water on Long Island, New York, New York Dept. Conservation, Water Power and Control Commission Bull. GW–1, 28 pp., 1936.

—that is, the only area where the gravel is to be expected; and third, that the pumpage from the Cretaceous beds is also fairly widely distributed, though there is none at the extreme west end of the island, where those beds have been entirely removed by erosion. The deeper Cretaceous beds, particularly the Lloyd sand, have been found to be especially valuable on the barrier beaches—Coney Island, Rockaway Beach, Jones Beach, and Fire Island Beach—where the Pleistocene beds are contaminated by salt water and the deeper beds, which are protected by clay blankets, yield water containing only 5 to 10 parts per million of chloride.

EFFECT OF PUMPING FROM WELLS.

The upper glacial deposits constitute a great reservoir in which a large quantity of water is stored. This stored water can be drawn on in times of drought or otherwise unusually heavy demand, but in the absence of covering clay beds to prevent recharge, the reservoir may fill up again rapidly when the pumpage is reduced or heavy rains come. In Nassau County since 1903 about 720,000,000,000 gallons of water have been used for public supply, of which nearly 95 per cent. has come from these upper beds. This is equivalent to a depth of water of about 13 feet over the entire county, and on the assumption of an effective porosity as high as 33 1–3 per cent. it would equal a body of water saturating the sand to a depth of 40 feet. In spite of the removal of so large a quantity of water the water table has at no time in the last 32 years dropped more than a few feet below its level in 1903. (Fig. 5.) The lowest level was probably reached about 1916, when pumpage was at a maximum, and another low level was reached in the dry years 1930 and 1931. Since that time the water level has risen, and in 1934 in many wells it was about as high as it had been at any time during the period of observation. If information as to the ground-water level in this area in about 1867 [14] has been correctly correlated with the more recent records,

[14] Kirkwood, J. P.: Report descriptive of the construction of the Brooklyn Water Works, in The Brooklyn Water Works and Sewers, contour map and profiles of the water table. D. Van Nostrand, 1867. The map has no date, and a state-

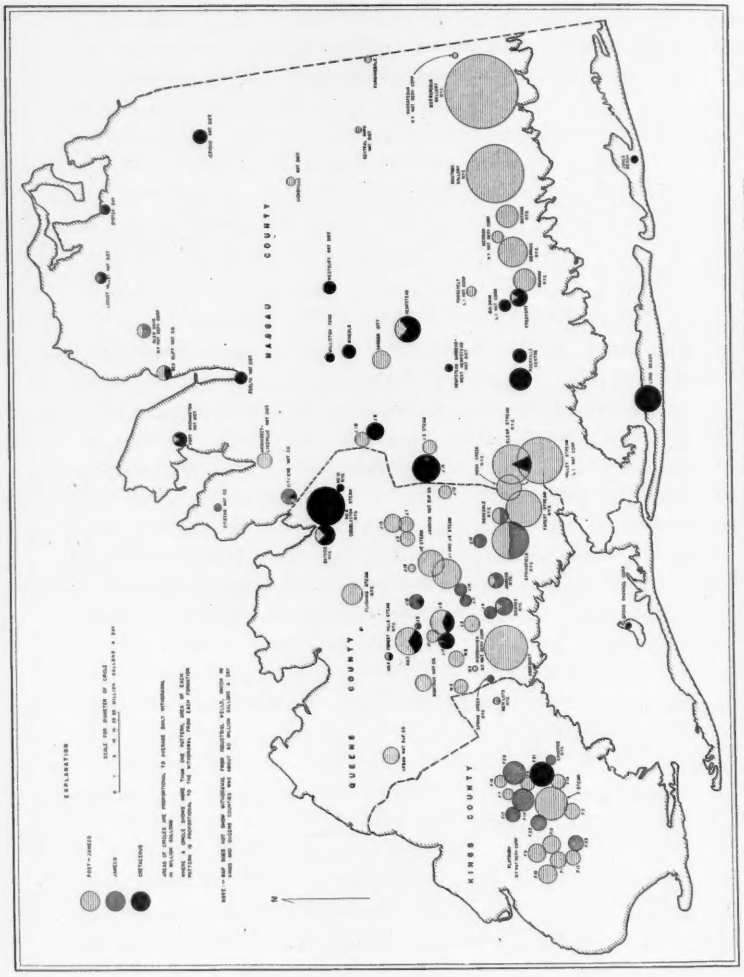

FIGURE 8.—MAP OF KINGS, QUEENS, AND NASSAU COUNTIES, N. Y., SHOWING AVERAGE DAILY WITHDRAWAL OF WATER FROM THE DIFFERENT SOURCE FORMATIONS AT PUBLIC SUPPLY PUMPING STATIONS IN 1930

the water table at that early date was several feet lower than at any time since 1903; and to judge from the records of precipitation it was probably even lower a few years earlier, at the end of a series of years longer and drier than any experienced in this area since that time.

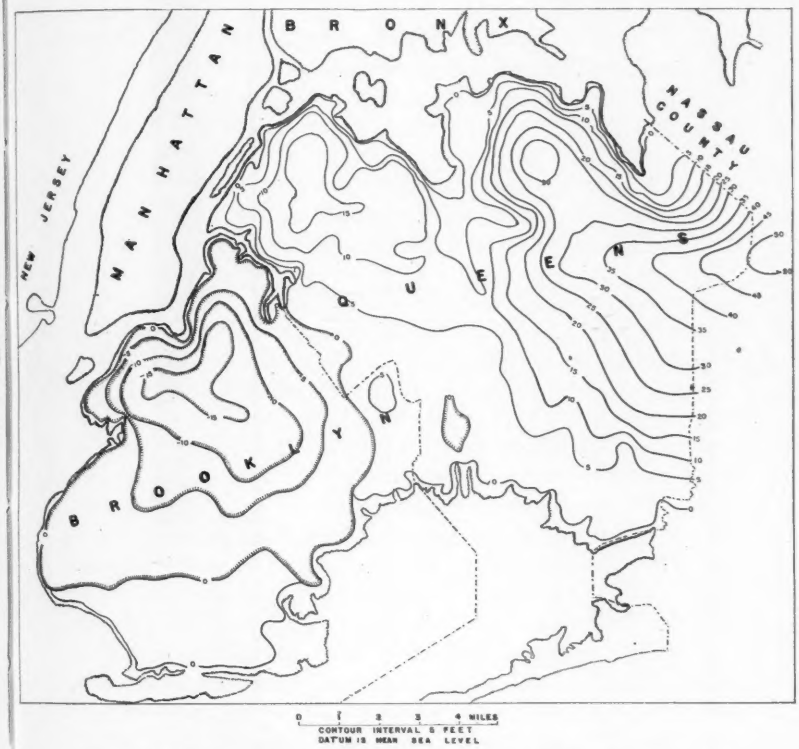

FIGURE 8.—MAP OF KINGS, QUEENS, AND NASSAU COUNTIES, N. Y., SHOWING AVERAGE DAILY WITHDRAWAL OF WATER FROM THE DIFFERENT SOURCE FORMATIONS AT PUBLIC SUPPLY PUMPING STATIONS IN 1930

FIG. 7. Map of Brooklyn and Queens boroughs, Long Island, showing contours of the water table, 1932–1933.

ment on page 59 suggests that the field data may have been collected in the winter of 1859–60 or not later than January, 1861. See also Leggette, R. M.: Long time records of ground-water levels on Long Island, New York. Am. Geophysical Union Trans., 1936, Part II, pp. 341–344, 1936.

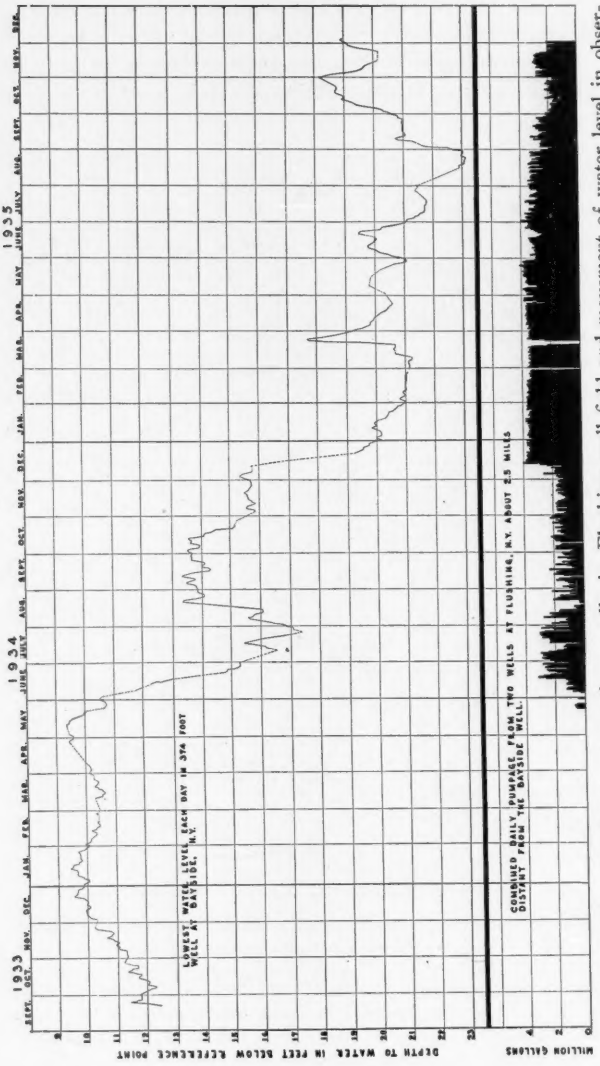
1933
1934
1935
SEPT. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC.
DEPTH TO WATER IN FEET BELOW REFERENCE POINT
LOWEST WATER LEVEL EACH DAY IN 374 FOOT WELL AT BAYSIDE, N.Y.
COMBINED DAILY PUMPAGE FROM TWO WELLS AT FLUSHING, N.Y. ABOUT 2.5 MILES DISTANT FROM THE BAYSIDE WELL
MILLION GALLONS

FIG. 8. Graphs showing pumpage from wells in Flushing well field and movement of water level in observation well of abandoned Bayside well field. The altitude of the reference point of the well is 11.04 feet above mean sea level.

In contrast to conditions in Nassau County, in parts of Brooklyn, where the pumpage has exceeded a rate of 4,000,000 gallons a day per square mile of drainage territory, a deep depression in the water table has developed.[15] It is now about 40 feet lower than in 1903 and about 25 feet below sea level, and the water table appears to be dropping slowly. The pumpage in this area is obviously much in excess of the safe yield of the beds. A distinctly unfavorable condition here is that because large areas are covered by buildings and pavements the opportunity for recharge is much less than in the open country. As a result of the heavy pumpage, salty or brackish water is pumped from many wells. The distribution of the salt water, however, is somewhat irregular, probably in part because of the irregular and as yet not entirely determined distribution of protective patches of Gardiners clay and intervening erosion channels.

In contrast to the upper glacial deposits, the deeper sands that lie beneath the clay beds and are under artesian pressure, although they have large storage capacity, act primarily as pipe lines to carry water from the relative small intake areas to areas of withdrawal. Accordingly, the factor controlling the safe yield of these beds is not the quantity of water available at the intake, which may be large, but the capacity of the beds to transmit the water from the area of intake to points of withdrawal. The loss of head, due to friction, even in beds that yield water freely, is large, and this loss of head may be effective for considerable distances from the area of withdrawal. For example, when wells drawing from the Lloyd sand in the Flushing field of the City of New York Department of Water Supply, Gas, and Electricity are pumped at a rate of about 3,500,000 gallons a day, the water level in a well in the abandoned Bayside well field, more than 2

[15] Laase, W. F.: Sub-surface water supply of western Long Island and its utilization. Municipal Eng. Jour., map. p. 24, 1934. Fig. 7 is based on a map accompanying this paper that was prepared by Thomas H. Wiggin, consulting engineer for the New York Water Service Corporation, in cooperation with officials of the New York Dept. of Water Supply, Gas, and Electricity, and consulting engineers for the Jamaica Water Supply Company. On this map at several places, zero contours are united in a manner that seems contrary to the usual idea of the way in which contours are drawn. These contours are drawn as on the original map of Wiggin.

FIG. 8. Graphs showing pumpage from wells in Flushing well field and movement of water level in observation well of abandoned Bayside well field. The altitude of the reference point of the well is 11.04 feet above mean sea level.

miles to the east, drops about 12 feet (Fig. 8), and the area of influence of the pumping wells undoubtedly extends several miles farther.[16] The significance of this fact, which is supported by observations elsewhere on the island, is that heavy pumping in one locality may affect the static head in another locality several miles away. Furthermore, because of the presumable connection between the upper and lower beds in some localities this effect may be transmitted either to higher beds where water-table conditions exist or to lower beds which may be in part under artesian pressure. This condition may be expected particularly in parts of Brooklyn, where the Gardiners clay has been found to be absent and where the clay above the Lloyd sand has been removed by erosion of the Sound River Valley.

CONCLUSION.

For several reasons, but particularly because of more favorable conditions of recharge, it seems desirable that future large developments of ground water on Long Island should be made mainly in the upper glacial deposits and that the deep Cretaceous beds, especially the Lloyd sand, should be reserved for development in certain areas where the upper beds are not available because of salt-water contamination, as on the barrier beaches, or because of other conditions.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
April 2, 1937.

[16] In March, 1937, when this paper is being submitted for publication, information has been received that a change in head of more than 10 feet in a well 3.2 miles, and of about 2 feet in a well 7 miles, respectively, from wells yielding 2 to 4 million gallons a day, resulted when the wells were shut down.

GEOLOGY OF THE MONARCH AND KICKING HORSE ORE DEPOSITS, BRITISH COLUMBIA.

E. A. GORANSON.

ABSTRACT.

The Monarch and Kicking Horse ore deposits in Yoho Park, B. C. represent former connected ore-runs separated by the subsequent valley-cutting of the Kicking Horse river. The "telethermal" deposits consist of lead-zinc ores formed by replacement of brecciated, crystalline, Cambrian dolomite. The brecciation resulted from fracturing of competent beds during anticlinal folding and afforded channelways for first, the dolomitizing solutions and second, for metallizing solutions of igneous derivation. The lead-zinc ratios indicate that zinc was more mobile than lead.

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INTRODUCTION.

THE Monarch and Kicking Horse ore deposits, consisting of sphalerite-galena replacement "runs" in brecciated crystalline dolomite, occur in the middle Cambrian carbonate rocks of Mount Stephen and Mount Field in the Yoho National Park, British Columbia. The Monarch deposits outcrop on the precipitous north slope of Mount Stephen on the south side of the Kicking

Horse river, and the Kicking Horse deposits outcrop on the south side of Mount Field on the north side of the river. The two deposits are similar mineralogically and probably had in the Kicking Horse valley a common junction which has been removed by erosion. The "runs" vary from flat-lying to a dip of about 12 degrees and in general are fairly uniform in dip along their footwall for a greater part of their length. Most of this paper pertains to the Monarch mine, which has been studied during part of the period of ore extraction. The partially developed Kicking Horse deposits have not yielded the same opportunity for study.

The Monarch mine is in close proximity to the main line of the Canadian Pacific Railway which follows the southern side of the Kicking Horse valley and passes close to the base of Mount Stephen, and to the main highway between Golden, British Columbia, and Banff, Alberta. The town of Field lies about 3 miles to the southwest. The elevation of the main mine portal is 5,010 feet above sea level and the portal is connected to the mill, adjacent to the railway track, by a Riblet jig-back aerial tramway which has a drop of 600 feet in a horizontal distance of 1,500 feet. The outcrops of the ore bodies range from 4,900 feet to 5,300 feet above sea level.

Mounts Field and Stephen lie near the western flank of the Rocky Mountains and respectively form parts of the north and south walls of the glacially-sculptured Kicking Horse valley. The mountains defining the valley are alpine in character, with jagged and knife-edged ridges, steep and commonly precipitous slopes, high cliff glaciers, and castellated crags. They rise to heights of 8,000 feet or more than 10,000 feet above sea level; Mount Stephen (10,495 feet) towers 6,500 feet above the fluvial-graded floor of the Kicking Horse valley. Mount Field (8,655 feet) is less imposing than Mount Stephen.

The ground plan of Mount Stephen is rudely triangular in shape and is the consequence of subaerial erosion along two southerly-converging faults (Fig. 1). On the east the mountain is defined by the Monarch creek valley which has been eroded along the Stephen-Cathedral fault, and on the southwest by a

valley that follows the curving Stephen-Dennis fault; both valleys head in cirques and are separated from adjacent valleys by high knife-edged divides. The Kicking Horse valley, defining the north side, is transverse to the structure of the rocks and probably has been eroded along a shear zone. Mount Field is part of a northerly-trending ridge and is defined on the east by the Stephen-Cathedral fault and the Yoho valley, and on the west by a northerly-trending fault and Burgess pass.

HISTORY.

In brief, the inception of the Monarch mine began with the construction of the Canadian Pacific Railway through the Rocky Mountains. Galena float, found in the Kicking Horse valley at the base of Mount Stephen by construction men, led to the staking of the East Monarch outcrop in the fall of 1884. It is of interest to note that the Monarch mine has the distinction of being the first producing metalliferous mine in the Canadian Rockies.

Up to the year 1912 approximately 2,400 tons of ore were reported to have been mined from the East Monarch. In that year a 75 ton mill was erected and ore was mined and milled intermittently to 1924; during this interval 40,015 tons were reported to have been mined. In 1916 the outcrop of the West Monarch ore body was discovered on the cliff and a small tonnage of ore was mined from this body. The Kicking Horse ore bodies were discovered later and until recently have been practically neglected.

In 1928 the Base Metals Mining Corporation, Ltd., was formed to develop and mine the Monarch and Kicking Horse ore bodies. A modern 300 ton differential flotation mill was erected and began operations in the fall of 1929. Mining and milling were carried on intermittently until December, 1935, when the Monarch ore reserves were exhausted. During this interval 256,500 dry tons of ore assaying Ag. 1.59 ozs., Pb. 9.7 per cent., Zn. 12.6 per cent., per ton, were mined and milled, the bulk coming from the West Monarch ore body. Since exhaustion of the Monarch ore bodies, exploration and development have been carried on with some success.

GENERAL GEOLOGY.

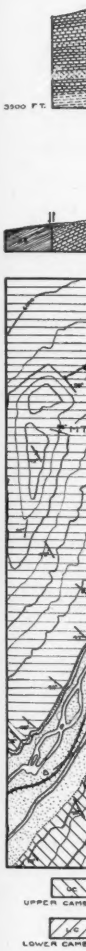
The general geology of the Field Map-area, which embraces the Monarch and Kicking Horse mines has been worked out by Allan and his report [1] deals in a general way with the rocks in the vicinity of the mine. Part of the following material on general geology has been taken from Allan's report.

Mount Stephen and Mount Field consist mainly of middle Cambrian carbonate rocks with lower Cambrian quartzites exposed at their bases and a small capping of upper Cambrian carbonate rocks at the summit of Mount Stephen (Fig. 1). Structurally the two mountains are part of a slightly dome-shaped, NNW-trending anticline which has been transected by the Kicking Horse valley (Fig. 1, sect. *AA'*). The gently arched axis of the anticline plunges slightly to the north and to the south and lies a short distance west of the summits of Stephen and Field; the dip of the limbs of the anticline varies from horizontal to 50 degrees and averages about 20 degrees. On each side of the axis lies a major normal fault with steep to vertical dips. On the east is the Stephen-Cathedral fault with a vertical displacement of about 3,000 feet and on the west is the Stephen-Dennis fault with an unknown displacement. A short distance to the east of the anticlinal axis is a vertically-dipping normal fault, with a vertical displacement of about 400 feet, which joins the Stephen-Dennis fault to the south.

The lower Cambrian rocks consist mainly of banded pure and impure quartzites with some arenaceous carbonate beds. The contact with the conformable middle Cambrian carbonate rocks is not sharp and the quartzites grade into the carbonate rocks. The quartzites, in thin section, are seen to be composed of interlocking quartz grains, carbonate, some muscovite, some fresh orthoclase and albitic plagioclase, and a few grains of brown tourmaline, and zircon.

The middle Cambrian has been subdivided by Walcott into

[1] Allan, John A.: Geology of the Field Map-area, B. C. and Alberta. Can. Geol. Surv., Mem. 55, 1914.



FIG

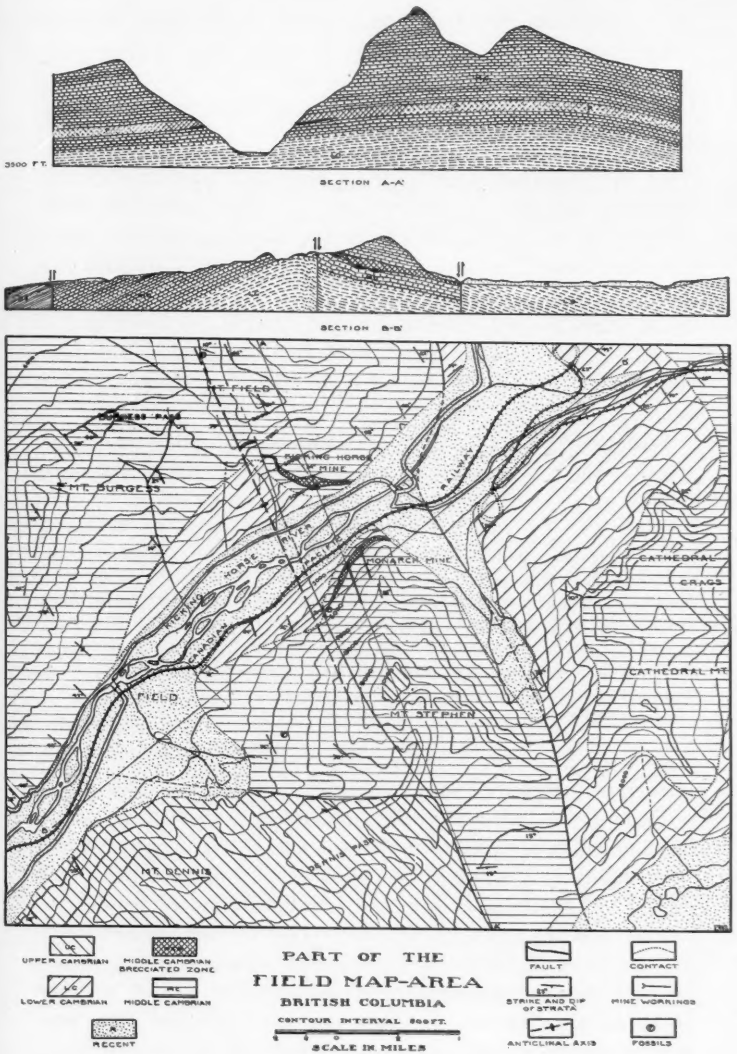


FIG. 1. Geological and contour map of part of the Field map-area. Modified from Map 142A, Geological Survey of Canada.

three formations largely on the basis of fossiliferous evidence. These formations are as follows;

Eldon	2,728 feet	
Stephen	640 feet	(562 feet on Mount Stephen)
Cathedral	1,595 feet	

They are composed dominantly of magnesia- and lime-bearing, light-gray to black, crystalline carbonate beds containing some arenaceous and argillaceous material. Commercial ore bodies have been found, to date, only in the lowest, the Cathedral formation, although small amounts of mineralization have been found in the lower Cambrian quartzites and in the lower part of the Eldon formation on Mount Stephen. The Stephen formation contains the famous Ogygopsis shale which on Mount Stephen is about 150 feet thick and has yielded 32 species of fossils.

Stratigraphically the Cathedral formation in the vicinity of the ore deposits consists, in ascending order, of the following members;

	Thickness
Light to dark-gray, medium-grained, banded dolomite	700 to 875 ft.
Light to medium-gray, medium-grained, altered zone	400 to 0 ft.
Dark-gray and black, fine-grained, thin-bedded dolomitic limestone	80 to 300 ft.
Medium-gray, medium to fine-grained, oolitic carbonate (dolomitic mainly)	100 ft.
Medium-gray, fine-grained, argillaceous dolomitic limestone	175 ft.
Black carbonatized argillite	150 ft.
Lower Cambrian quartzites	

As viewed from the Kicking Horse valley, a zone of altered-looking carbonate rock passes up through the Cathedral formation on Mounts Stephen and Field generally at a small angle to the bedding and rises to the west (Figs. 1 and 2). In contrast to the surrounding rock which is bedded or banded and weathers gray or black, the alteration zone is practically devoid of banding or bedding and has a pinkish caste and rubbly-looking appearance on the weathered surface. A few oriented inclusions of the underlying thin-bedded member and of the overlying banded dolomite are seen within the zone generally near the lower and upper contacts respectively. Along the valley, the zone is exposed for a

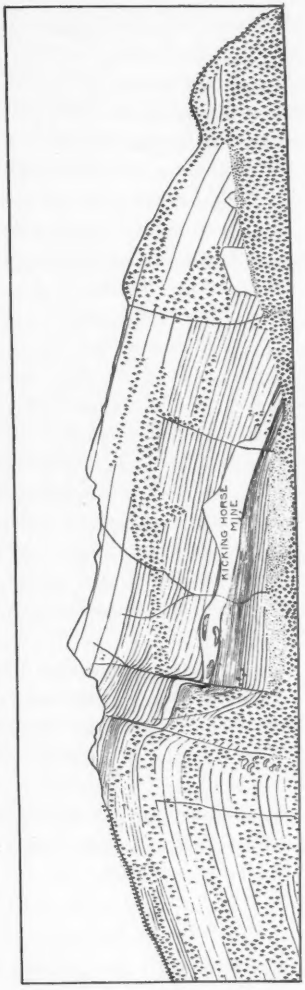


FIG. 2. Sketch of Mount Field showing the alteration zone (blank) and the location of the portals of the Kicking Horse workings.

length of about 4,000 feet on Mount Stephen and for a length of about 4,500 on Mount Field On Mount Stephen the zone tapers and disappears to the west and terminates in a cliff on the east. On Mount Field it also tapers and disappears to the west and on the east it disappears under the talus, covering the valley floor, somewhat reduced in thickness; further east on Mount Field a few patches of alteration extend above the talus and indicate that the zone probably increases in thickness again and continues to the Stephen-Cathedral fault. In a direction transverse to the valley the zone is exposed only for a distance of about 500 feet before it disappears under the talus. The zone has a maximum thickness of about 400 feet and this thickness is attained directly above the ore bodies, which lie close to the base, and entirely within, the alteration zone. The lower contact of the zone appears from a distance to be fairly regular for most of its length and although it, in general, cuts up through the thin-bedded dolomitic limestone, it also follows, in part, the minor structures in this member. The upper contact of the zone is irregular and undulating. Most of the zone is inaccessible for close observation as it outcrops on steep to precipitous cliffs. No evidence of this zone can be noted on Mounts Cathedral and Ogden, which consist mainly of middle Cambrian rocks and lie a short distance to the east of Mounts Stephen and Field.

The upper Cambrian series consists essentially of thin-bedded and massive carbonate rocks and shales, and has been divided into five formations. Part of the upper Cambrian series in the vicinity of the Ottertail river has been highly sheared and metamorphosed.

Recent deposits consisting of talus, glacial debris, gravel, sand, and silt, cover the bottom of the Kicking Horse valley and extend for some distance up into the tributary valleys.

MINE GEOLOGY.

The Monarch and the Kicking Horse deposits lie close to the base of the alteration zone in the brecciated portion immediately above minor structures in the thin-bedded underlying member.

The lower contact of the alteration zone, when examined in the underground workings and accessible points on the cliffs, is seen to be somewhat irregular but, in general, it rises fairly uniformly to the southwest; the contact rudely follows the shapes of the minor structures in the thin-bedded underlying member and does not cut across these features as would be expected if it followed a shear. In places, the lower contact is sharp, but commonly it is gradational and the thin-bedded underlying member grades into the altered rock; at points a medium- to coarse-grained speckled dolomite, much resembling a granite in appearance, separates the two. The footwall contacts of the ore bodies range from 2 feet to 40 feet above the lower contact of the alteration zone and no commercial ore has yet been found except close to this contact.

The brecciation occurring at the base of the alteration zone is present throughout most of the length of the zone and appears to be directly related to the minor structures shown by the underlying thin-bedded member. Above the minor synclines, with which the ore bodies are associated, the brecciation is most pronounced and generally extends from 15 feet to 80 feet above the thin-bedded member. The brecciation grades, on top, into light-gray structureless dolomite, which, in turn, grades into banded, gray to black crystalline dolomite.

The brecciated rock consists of dark- to medium-gray, angular to sub-angular and occasionally rounded fragments of dolomite that are enclosed in a white dolomite matrix. The fragments vary from fine- to medium-grained and range up to 12 inches across and show varying degrees of replacement by later carbonates. The breccia appears to have formed mainly by a shattering of the dolomite lying immediately above the minor structures in the dolomitic limestone and the fragments have little or no disarrangement from their original position. In the brecciated rock there are at least three ages of dolomite that have succeeded the original carbonate of the rock and are as follows; a fine-grained dark dolomite that replaced the fragments completely, a light-gray dolomite that replaced the above dolomite partially or completely, and a medium- to coarse-grained white dolomite

that replaced in part the other two carbonates and veined and cemented the fragments. A partial analysis of the brecciated-dolomite rock is given in Column 1, Table 1.

TABLE 1.

	1.6	2.6	3.6
CaO	30.5	27.7	42.5
MgO	19.1	16.8	5.9
FeS_2	3.2	2.1	1.3
FeO	1.1	4.5	—
Insol.	0.2	5.5	10.2
CO_2 (calc.)	45.4	42.8	39.9
	99.5	99.4	99.8

1. Partial analysis of the brecciated rock by J. P. Dick.
2. Partial analysis of the top of the dolomitic limestone member by J. P. Dick.
3. Partial analysis of the dolomitic limestone by L. Marple.

Remnants of bedding are found in a few places within the breccia in the form of fine-grained argillaceous lenses that have withstood alteration and brecciation.

The member underlying the ore deposits consists mainly of thin-bedded, fine-grained, crystalline dolomitic limestone. Near the contact with the alteration zone the rock may be brecciated for a few feet in depth and veined and cemented by white dolomite. For some distance from the contact the underlying member commonly has a chemical composition similar to the altered and brecciated rock although there may be no change in visual appearance (column 2, Table 1). Generally not more than 10 feet from the contact the composition changes to that of a dolomitic limestone (column 3, Table 1), which does not vary, except in an increasing amount of insoluble material, toward the base of the member.

Structure.

The ore bodies are associated with minor structures on the east flank of a slightly dome-shaped, N.N.W.-striking anticline. The Monarch deposits lie either in minor synclines or on the limb of a minor syncline whereas the Kicking Horse deposits lie in places where the limb has locally flattened to a nearly or quite horizontal

position. The trend of the minor synclines in general parallels the major axis of folding, which is north 15° west, whereas the flats may deviate somewhat from parallelism. A minor amount of cross-folding, roughly at right angles to the general trend, has occurred but appears to be unimportant in respect to the ore bodies.

The minor structures with which the ore bodies are associated are shown in detail only by the rocks underlying the alteration zone, as these and other minor structures do not persist up into the carbonate rocks overlying the alteration zone. Underground, very few workings cross-cut the strike of the minor structures in the dolomitic limestone, but sufficient data have been obtained from these workings and from diamond drilling to indicate that there is a definite spatial relation between the ore bodies and the structure. Further it appears that these minor structures are not continuous for any great distance along the strike and that the associated ore bodies are governed to a large extent by the length and breadth of the structures. In the Monarch mine three minor synclines have been explored so far, one of which is blind and the other two outcrop on the cliff. Two of these structures have ore in the synclines and the blind structure has ore on its west limb and pyrite in its trough. In the Kicking Horse it is not known whether the relation of the ore bodies to the "flats" holds throughout the length of the ore bodies because most of the exploratory work has been in the alteration zone where the structure is either lacking or obscure.

Fissures and Faults.—The ore bodies and the alteration zone are traversed by a number of fissures that are mostly vertical. Movement on them up to 2 feet has been recognized but in general it is slight or nil. A few of the fissures extend down into the lower Cambrian quartzites but most of them either stop at the dolomitic limestone or penetrate it for only a few feet. The fissures vary from narrow breaks to several feet in width and the latter are generally filled with carbonate rubble or gouge, and in places with "mountain leather." The fissures commonly curve along their strike and dip, and may branch or may stop and continue again a short distance further on. Some of the fissures

show striae along their walls but generally such details have been masked or obliterated by seeping waters. On the cliffs where the fissuring is the most severe the alteration zone is seen to attain its maximum thickness. The fissures in the Monarch mine may be rudely grouped into a north-south system and an east-west system and are mainly vertical. In the Kicking Horse, most of the fissures strike northeast and dip steeply southeast.

In general there is little relationship between the ore and the fissures but at places within the ore local enrichments occur at fissure intersections; minor shoots of ore may also project a few feet from the main body into the country rock along a fissure. In the vicinity of some of the fissures the ore may suddenly diminish in grade or may cease abruptly, to continue again on the other side of the fissure. In places the ore is slightly sheared near the fissures.

The fissures are probably all pre-ore and probably were formed at different times by stresses that have been manifested by folding, faulting, and dolomitization. Minor post-ore adjustments have taken place along some of the fissures and are responsible for local slight amounts of faulting of the ore.

The Ore Bodies.

In the Monarch mine there are two independent parallel ore bodies, called respectively East and West Monarch, which outcrop at elevations of 5,123 feet and 5,324 feet. These bodies strike about north 15° west and are 660 feet apart at the outcrops (Fig. 3). Both bodies rise at an angle of 8 degrees to the south, which is slightly steeper than the bedding of the underlying dolomitic limestone (Fig. 4). At the outcrop, the West Monarch body is 50 feet higher stratigraphically than the East Monarch body. In the Kicking Horse mine the deposits are known as the No. 1 and the No. 2 bodies and outcrop at elevations of 4,927 and 5,027 feet respectively. The No. 2 body is 210 feet west of the No. 1 body at the outcrop and is slightly higher stratigraphically. The No. 1 body strikes about north 17° west and plunges about 12 degrees to the north; the No. 2 body strikes north 45° west

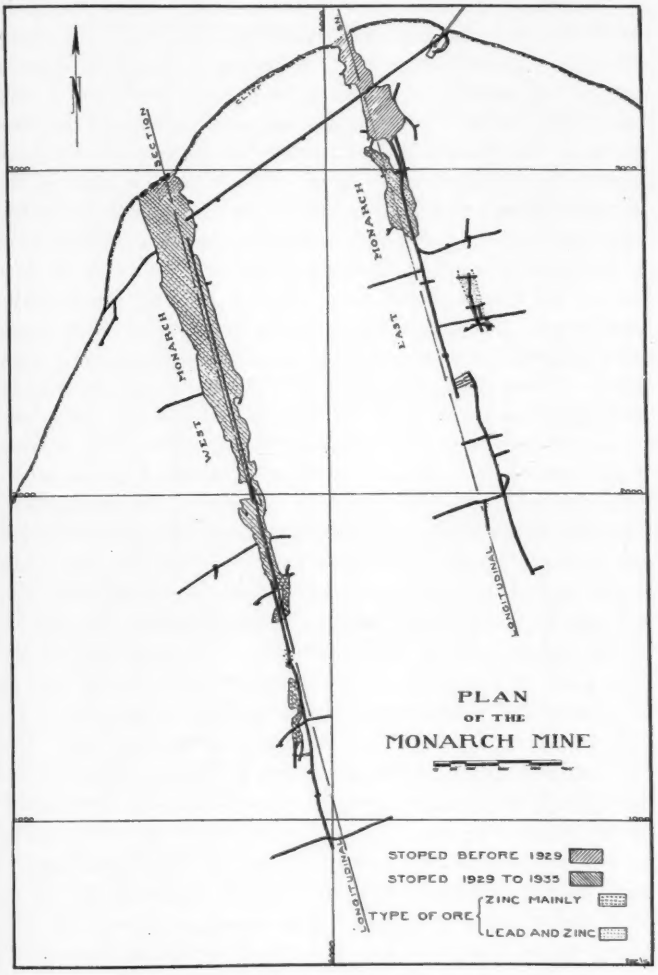


FIG. 3. Plan of the Monarch mine.

and is almost horizontal. The contacts of the Monarch and Kicking Horse ore bodies with the country rock are commonly sharp, although somewhat irregular in outline, and in general there is little or no change in the grade of the ore from side wall to side wall. The side and hanging walls are not dependent on the brecciation as the brecciation is commonly as pronounced for some distance beyond the ore as within. The footwall contact of the ore ranges from 2 feet to 40 feet above the contact with the underlying thin-bedded member and its position appears to be dependent on the degree of brecciation of the alteration zone above the contact. With the exception of the No. 1 Kicking Horse body, which is only partially explored, the ore bodies attain their maximum cross-section near or at the outcrop and taper along their strike. Where the bodies attain a thickness of over 20 feet the ore is generally rudely stratified, with galena and sphalerite making up the lower layer, and sphalerite with a little galena making up the upper layer. In places high-grade lenses of galena carrying a little sphalerite occur along the footwall of the ore deposits.

In the West Monarch, practically continuous mineralization was followed inward for 1,760 feet from the outcrop. The greater part of this body was mined except for a distance of 165 feet near its southern end where the mineralization was too irregular and too thin to be commercial. The main part of the body, 1,400 feet in length, had a maximum width of 158 feet at the outcrop and tapered somewhat irregularly to the south. Its thickness varied from 8 to 55 feet and averaged 19 feet. The body consisted of sphalerite and galena for 1,300 feet from the outcrop and then changed abruptly to sphalerite with little galena for the rest of its course. South of the non-commercial stretch, the body was mined for a further 180 feet and then the mineralization ceased abruptly. This latter portion averaged 25 feet in width and 9 feet in height. Approximately 226,500 tons (including an estimate of 8,000 tons mined by former operators) averaging Ag. 1.7 ozs., Pb. 10.5 per cent., Zn. 12.5 per cent., and 10,000 tons averaging Ag. 0.3 ozs., Pb. tr., Zn. 12.0 per cent., were mined from the West Monarch.

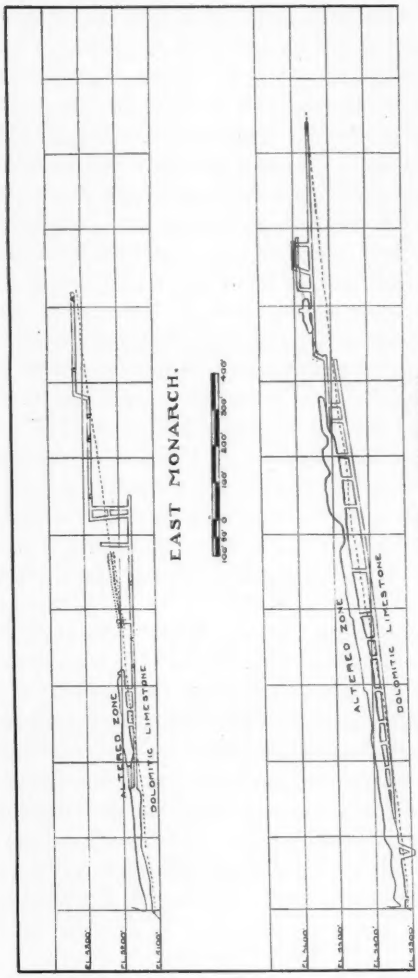


FIG. 4. Longitudinal projections of the East and West Monarch workings.

The East Monarch body is not as continuous and regular as the West Monarch and consists, so far as explored, of three distinct bodies that are connected by pyrite mineralization carrying small quantities of galena and sphalerite. Two of the bodies lie on the same strike and are close together whereas the other is offset about 150 feet to the southeast. For convenience these three bodies are designated as the first, second, and third ore bodies, numbering from the cliff inwards. The first or outcropping body was opened for a length of 340 feet with an average thickness of 15 feet and a maximum width of 120 feet at its south end; it is reported that this body produced some 34,000 tons of ore (grade unknown). The second body practically adjoins the first and was opened for a length of 330 feet with an average thickness of 12½ feet and a maximum width of 90 feet at its centre. This body produced 28,000 tons averaging Ag. 1.1 ozs., Pb. 7.0 per cent., Zn. 13.5 per cent. The third body is now being developed and appears to have a width of 40 feet and a thickness of 10 feet; grade from muck samples averages Ag. 1.3 ozs., Pb. 8.0 per cent., Zn. 19.5 per cent. To the south, and directly in line of strike with the first and second ore bodies, is an irregular zone of disseminated galena with a little sphalerite, which has been partly explored for a length of 500 feet

The No. 1 and No. 2 Kicking Horse ore bodies have been drifted on respectively for 230 feet and for 760 feet along their strikes. The No. 1 body averages 40 feet in width, 15 feet in thickness, and the mineralization consists of sphalerite with a small amount of galena, running about 0.5 per cent. Pb., 11.0 per cent. Zn. The No. 2 body achieves a maximum width of 170 feet at the outcrop and tapers gradually to the north; its thickness at the outcrop is about 15 feet. For 270 feet from the outcrop the No. 2 body averages about 4.0 per cent. Pb., 12.0 per cent. Zn, while further to the north the grade is somewhat lower.

Mineralization.

The mineralogy of the deposits is simple and consists chiefly of hypogene sphalerite, galena, pyrite, and dolomite, with minor

amounts of chalcopyrite, quartz, barite, and silver; very small percentages of arsenic, antimony, bismuth, and manganese, and a trace of gold, have been found in the concentrates. The sulphides have formed essentially by replacement of the breccia fragments and of the white dolomite. Pyrite, either massive or disseminated, is generally associated with the ore bodies and is commonly segregated along the east wall of the deposits. The sequence as determined from polished sections is as follows, from oldest to youngest, dolomite, quartz, pyrite, sphalerite, galena. Small horses of waste occur at places in the ore bodies; they are generally unbrecciated but dolomitized residuals of the country rock. Small vugs are fairly numerous both within the ore and in the country rock and are generally lined with etched rhombohedra of dolomite on which are perched small pyritohedrons of pyrite.

A number of supergene products have formed, generally near and around fissures. These products include limonite, selenite, calcite, anglesite, and copiapite. The outcrops of the ore bodies show very little oxidation because erosion of the vertical outcrops has taken place fairly rapidly.

Dolomite.—As previously mentioned, there are at least three ages of dolomite of which the last was the white dolomite; the two earlier stages appear to be closely related in age. The white dolomite is believed to be closely associated with the sulphides in time of formation and is veined and replaced by these later minerals. In places are found veinlets of a fibrous dolomite (elongated along the C-axis), which are cut by veinlets of the white dolomite. Some tiny veinlets of calcite are later than the ore and are probably supergene.

Pyrite.—Pyrite occurs mainly along and near the east wall of the ore bodies and connecting bodies of ore, and to some extent along and near the west wall and within the ore. No satisfactory reason can be advanced why the pyrite has been formed along the east wall of the ore bodies. The only crystal form found in the vicinity of the ore is that of the pyritohedron which ranges up to one inch across; nodular pyrite has been found in one locality.

In polished section some of the pyrite crystals are seen to be concentrically zoned. One polished section shows a few minute grains of a white, anisotropic mineral associated with pyrite, which were too small to be identified.

Sphalerite.—Sphalerite occurs in a number of color varieties, light-yellow, brown, brownish-red, and honey yellow, and is mostly transparent to translucent. The brownish-red variety is commonly fine- to medium-grained in texture and generally replaces the breccia fragments whose texture it simulates; in a few places it inherits the original bedding in the rock. The other color varieties are generally medium- to coarse-grained and replace the white dolomite. The sphalerite is fairly uniform in its distribution throughout any given ore body. Crystal forms of sphalerite are occasionally found projecting into vugs. All the varieties of sphalerite are low in iron, 0.5 per cent. or less, and are free from cadmium.

Galena.—Galena commonly occurs intimately associated with sphalerite and also as high-grade irregular masses along the footwall of the ore bodies. The galena varies from fine- to coarse-grained and appears to be slightly sheared especially near the fissures. Small patches of galena and rarely of sphalerite have been found in the underlying thin-bedded member and are generally associated with veinlets of white dolomite.

Silver.—The ore contains a small quantity of silver, which ranges from traces to 12 ozs. per ton. In milling, 80 per cent. of the silver separates with the galena concentrate, 10 per cent. with the sphalerite concentrate, and 10 per cent. remains in the tails. It is not yet known how the silver occurs, but as channel samples taken at 5-foot intervals throughout the ore bodies show no fixed relation between the amounts of silver, lead, and zinc present, it seems probable that the silver occurs as an independent mineral which has escaped detection.

Chalcopyrite.—Small amounts of chalcopyrite occur at several localities in the Monarch mine, generally associated with pyrite and white dolomite. In polished sections, small patches of chalcopyrite were noted within galena.

Barite.—Barite has been found in minor quantities in a few places near the ore bodies and in the underlying dolomitic limestone. It occurs either as a vug filling or as irregular patches in the country rock and is generally associated with white dolomite and galena.

Quartz.—Quartz is present to a small extent either in vugs or as irregular small masses within or near the ore bodies. In the vugs the quartz occurs as well developed, singly or doubly terminated crystals perched on etched dolomite rhombohedra. The irregular masses within the ore are in places cut by stringers of galena.

Limonite.—"Limonite" is developed in considerable quantities in fissures and in cavities close to fissures. It is very porous and has formed from the oxidation of pyrite.

Selenite.—Supergene selenite forms in cavities and along fissures and is associated with pyrite and limonite. In the cavities the selenite occurs in well crystallized forms up to 1½ inches in length; the crystals generally contain inclusions of limonite.

Calcite.—Calcite occurs within the alteration zone in tiny crystals lining cavities and in narrow veinlets. Scalenohedral forms of calcite up to 2½ inches in length project into cavities in the dolomitic limestone at or near the surface.

Anglesite.—Minute crystals of anglesite were found in one locality coating crystal faces of galena which were projecting into a vug. Other oxidation products of galena, and of sphalerite, are probably present but have not been recognized.

Copiapite.—A hydrous ferric sulphate, copiapite, forms in small quantities within caves in massive pyrite at the surface. The copiapite is sulphur yellow in color and occurs as loose incoherent masses encrusting pyrite.

Rock Alteration.

The wall rock in the neighborhood of the ore bodies shows little change beyond dolomitization, which occurs throughout the alteration zone and most of the middle Cambrian section as well. The alteration zone in which the ore bodies occur is, however,

structureless in contrast to the banded or bedded rocks lying above and below the zone. Pyrite, although present to some extent throughout the carbonate rocks of Mounts Stephen and Field, occurs more abundantly in the alteration zone. Also small patches of green chlorite (related to sheridanite[2]) appear to be localized to the zone. "Mountain leather" has been found in some of the fissures and cavities within the alteration zone but at some distance from the ore bodies. The relation of the "mountain leather" to the ore is not known but the two probably have a like origin.

GENESIS OF THE DEPOSITS.

The middle Cambrian section in the vicinity of the deposits consists mainly of carbonate rocks which, within the Cathedral formation, show a gradual transition in sedimentation from the underlying lower Cambrian quartzites to pure carbonate rocks. These carbonate rocks, prior to folding, were first crystallized, probably by static metamorphism, and then dolomitized. The dolomitization appears to have been somewhat preferential in its action, altering in the main the upper and purer carbonate beds and leaving the lower and more muddy carbonate beds little changed. The lower limit of the dolomitization is believed to have roughly coincided with the lower contact of the alteration zone as now exposed; it possibly may have been localized by a low angle shear cutting up through the carbonate beds and which has been entirely obliterated by the later geologic events. Some change in volume undoubtedly occurred and was probably adjusted by the formation of tension fissures and cavities. Folding then occurred, culminating in the formation of the Stephen-Field anticline and the minor folds and flats on the flanks of the anticline. During the folding the lower more incompetent and impure beds yielded by folding to form the minor structures, whereas the overlying more competent dolomitized beds fractured and shattered near the minor flats and folds; tensional stresses then prevailed and led to the formation of the normal faults on the flanks of the anticline and near the axis of the anticline. The final stage of dolomitization directly

[2] Identification by Professor E. S. Larsen.

preceded the introduction of the ore-bearing solutions into the more permeable zones immediately overlying the minor structures. This resulted in the white dolomite by filling and replacement, and the ore bodies essentially by replacement.

The solutions forming the Monarch and Kicking Horse deposits are believed to have migrated from a locus in the Kicking Horse valley and travelled through the shattered and consequently more permeable zones in which the ore deposits are found. The solutions may have arisen from along or near the Stephen-Cathedral fault as there is some indication that the alteration zone attains its maximum thickness on the southeast side of Mount Field close to the fault. The individual ore deposits or "runs" were all apparently fed from within themselves as there is a decided lack of ore connections between either the East and West Monarchs or the No. 1 and No. 2 Kicking Horse ore bodies. Although the deposits are confined to the more permeable zones, the influence of the solutions was more far reaching and caused the formation of the alteration zone in which the ore bodies lie. The solutions migrated laterally and vertically from the channelways probably along the numerous fractures that occur above the thin-bedded dolomitic limestone; the result, mainly thermal, was a recrystallization of the carbonate rock together with the introduction of some pyrite and minor amounts of chlorite and probably "mountain leather."

The variation of the ratios of lead to zinc in the four ore bodies or "runs" has been pointed out and is probably due to the relative ease of movement of these two metals in solution. Of the two, zinc appears to be the more mobile and penetrated and formed in ground which had been little prepared for ore deposition. This appears to be illustrated by the West Monarch ore body, which changed abruptly along the strike from lead-zinc to zinc at a point that coincided with a change in structure from a syncline to a flat.

The nearest exposure of igneous rocks is in the Ice river, 17 miles south of the Monarch mine, where a laccolithic body of alkaline igneous rocks outcrops. In the sediments intruded by

that complex are a number of ore deposits that differ only mineralogically from the Monarch and Kicking Horse deposits by the added presence of pyrrhotite and arsenopyrite. The spatial relationship of the Ice river deposits to the complex implies a genetic relationship between the two, and thus probably there may be inferred an igneous origin for the Monarch and Kicking Horse deposits also. It appears to the writer that the entire area may be underlain by an igneous body of which the Ice river complex is the sole visible part. The age of the Ice river complex is not known; it intruded lower Ordovician sediments.

The mineralogy and wall rock alteration of the Monarch and Kicking Horse deposits indicate that they were formed under low physico-chemical conditions. In the intensity classification scheme of ore deposits, these deposits appear to have formed under conditions similar to those which have been ascribed by Graton [3] to his recently proposed telethermal zone. The depth at which the Monarch and Kicking Horse deposits formed is greater than the depth which Graton has suggested for the telethermal zone as there is a thickness of 5,500 feet of rock overlying the Monarch deposits on Mount Stephen.

ACKNOWLEDGMENTS.

The writer wishes to express his appreciation to Messrs. Arthur Notman, Basil Prescott, and W. H. Emens, especially, for many helpful discussions of the geological problems. To Professor L. C. Graton the writer is deeply indebted for a critical reading of this paper. Also the writer wishes to thank the Base Metals Mining Corporation, Limited, for permission to publish this paper.

BASE METALS MINING CORP.
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March 3, 1936.

[3] Graton, L. C.: The depth-zones in ore deposition. ECON. GEOL., vol. 28, pp. 547–551, 1933.

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DIFFUSION AND ITS RELATION TO ORE DEPOSITION.

STANLEY DUFFELL.

ABSTRACT.

The experiments performed show a similarity in the penetration of a dissolved salt into saturated and unsaturated specimens of the same rock; and indicate a more rapid penetration of the solvent part of the solution in the case of the unsaturated specimens.

In the saturated specimens, penetration is by diffusion. In the unsaturated specimens, penetration at first is by capillarity, but after the separation has taken place, the solute moves through the solvent-saturated part of the rock chiefly by diffusion.

Diffusion then is an important factor in both instances, and it is indicated that this process may play a more important role in the migration of solutions through rocks than is generally believed.

INTRODUCTION.

THE problems of diffusion are intimately linked with those of the migration of solutions through rocks. In the migration of solutions through rocks, two features are of interest; the movement in fractures and capillary openings, and the movement of constituents of solutions by diffusion. Probably the first process is the most important, but diffusion sometimes plays an important rôle.

An attempt has been made to compare the relative abilities of capillarity and diffusion to aid in the migration of solutions through rock interstices, and the factors affecting this movement. Experiments were performed in which solutions were allowed to penetrate saturated and unsaturated specimens and the degree of penetration measured over a similar period of time. It is not the intention to bring forward diffusion as the prime means of migration of dissolved substances but rather to point out the various circumstances in which diffusion plays a more or less important rôle in the process of mineral concentration.

For helpful advice and criticism given throughout the investigation, the writer wishes to express appreciation to Dr. E. S. Moore of the Department of Geology, University of Toronto.

FACTORS GOVERNING THE ENTRY OF SOLUTIONS INTO ROCKS BY CAPILLARITY.

The channelways for the movements of solutions through rocks are fractures, pores and capillary openings. Some openings are too large and some too small for capillarity to become effective, but it is active in most rocks.

In capillarity, the size of the opening is an important factor; the smaller the opening the greater the force.

According to their size, Van Hise [1] has classified these openings as follows:

(1) *Supercapillary Openings.*
  (*a*) Circular openings greater than .508 mm. in diameter.
  (*b*) Sheet openings greater than .254 mm. between the walls.

(2) *Capillary Openings.*
  (*a*) Circular openings .508 to .0002 mm. in diameter.
  (*b*) Sheet openings .254 mm. to .0001 mm. between the walls.

(3) *Subcapillary Openings.*
  (*a*) Circular openings less than .0002 mm. in diameter.
  (*b*) Sheet openings less than .0001 between the walls.

FACTORS GOVERNING THE PROCESS OF DIFFUSION

The term diffusion is generally applied to the process whereby molecules of a substance in solution move from places of higher, to places of lower concentration. Therefore a difference in concentration is a prime factor in transfer by diffusion.

That differences in temperature in the same solution will cause migration of molecules was demonstrated by Soret.[2] This migra-

[1] Van Hise, C. R.: A treatise on metamorphism. U. S. Geol. Surv. Mon. 47, p. 142, 1904.

[2] Soret: Ann. Chim. Phys., 1881. Cited by Whetman, W. C. D.: Theory of solutions, p. 376, Cambridge University Press, 1902.

tion is believed to be caused by diffusion. An increase in temperature will increase the rate of diffusion as was demonstrated by Sullivan and Sweet.[3]

Ionization is another factor that affects the process. Salts that ionize are found to diffuse more rapidly than salts that do not.

Besides these factors affecting diffusion in general, there are several that must be considered when a solution migrates through a rock. Absorption of material in solution by the rock grains will tend to lower the concentration of the solution at that point. When the salt in solution is precipitated by chemical reaction, the concentration of the solution, where precipitation has taken place will be less. In both the above mentioned instances diffusion will tend to move material to those places where concentration has been lessened.

Experiments with True Solutions and Various Rock Types.

Experiments were performed with a view to obtaining a comparison of the rate at which solutions of salts enter rocks by capillarity and by diffusion. Solutions were allowed to penetrate dry rocks and rocks saturated with water. In the first case the solution enters through pores and by capillarity, and in the second the contained salt enters only by diffusion.

Other experiments of a similar nature were performed to ascertain the power of dilute colloidal solutions to penetrate rocks along capillary openings, and to determine whether there was any separation between various parts of the solution and if so, the rate of separation.

The rocks used in the experiments varied from highly porous sandstones, to rocks such as marble with very low porosity. The porous rocks, such as Haddington Island andesite, and Cataract sandstone were easily penetrated by the solutions. Both of the above mentioned rocks have a high permeability, water completely permeating a one inch cube in less than an hour.

[3] Sullivan, J. D., and Sweet, A. J.: Factors governing removal of copper from leached ores. U. S. Bur. Mines Tech. Paper 453.

DESCRIPTION OF ROCKS USED IN EXPERIMENTS.

(1) Fine grained white marble from Calabogie, Ontario. A recrystallized Grenville limestone of even grain and white color. It has a porosity of 0.342 per cent.

(2) Cataract sandstone from Orangeville district, Ontario. Fine to medium grained, consisting mainly of quartz, but containing a few grains of feldspar. It is greyish in color and has a porosity of 11.9 per cent.

(3) Recrystallized limestone from Renfrew county, Ontario. A very coarse grained recrystallized limestone, white in color, but with a greyish tinge in places. The rock has a porosity of 0.391 per cent. and is relatively impervious.

(4) Sandstone from Oneida township, Ontario. Composed chiefly of quartz with a few grains of feldspar. The rock is brown in color, of medium grain and is very loosely cemented. It has a porosity of 20.00 per cent.

(5) Magnesian limestone from Oneida township, Ontario. Very fine grained, yellow to light brown in color. Porosity 14.7 per cent.

(6) Andesite from Haddington Island, British Columbia. Light yellow in colour. Homogeneous, fine grained groundmass. Porphyritic with a few phenocrysts of feldspar. Porosity 13.96 per cent.

The rocks used were apparently free from cracks of any kind.

SOLUTIONS.

The following solutions were used in the experiments:

(1) A cupric sulphate solution containing 5 grams of $CuSO_4 . 5H_2O$ per 100 c.c. of water.

(2) A ferric chloride solution containing 10 grams of $FeCl_3$ per 100 c.c. of water.

(3) An aqueous solution of red dye eosin.

(4) An aqueous solution of sodium sulphide.

These solutions were chosen either because they left a distinctive mark where they penetrated the rock, or because treatment with some other solution brought out a distinctive mark. Cop-

per and iron salts give a black precipitate when treated with sodium sulphide, and a distinctive mark showing the distance of penetration.

EXPERIMENTAL PROCEDURE.

Blocks of the rocks tested were cut into approximately one-inch cubes, but in some cases the cubes were larger. Two similar blocks of the same rock were made and one immersed in water until it became saturated. The saturated and unsaturated blocks were then placed in the test solutions. In the case of the more permeable rocks the penetration was measured, in most instances, at the end of every twenty-four hours, but with those less permeable the first penetration was not taken in some cases until the end of forty-eight hours.

After the time of the experiment had elapsed the specimens were taken out of the solutions and their surfaces dried. This was done to prevent any creeping of solutions across the freshly broken surfaces. When the eosin dye was used the blocks were broken open and the penetration measured directly. Where solutions of the salts of iron and copper were used the freshly broken surface was dipped into a solution of sodium sulphide. The sodium sulphide reacting with the salts of iron and copper gave a dark coloration where the copper or iron had entered. This dark coloration showed up very distinctly in the light colored rocks such as the andesite from Haddington Island and the magnesian limestone from Oneida township, Ontario.

In the experiments with colloidal solutions and the various rock types, the same procedure was followed.

TABULATION OF RESULTS.

Haddington Island andesite treated with cupric sulphate solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
1	5	1	2
2	18	3	3
3	24	4	5
4	48	5	5
5	48	5	5
6	144	6	6
7	168	7	8

Fine-grained recrystallized Grenville limestone from Calabogie, Renfrew county, Ontario, treated with cupric sulphate solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
8	24	1	1
9	48	4	5
10	72	5	6

Cataract sandstone from Orangeville area, Ontario, treated with cupric sulphate solution.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.	Temp. and Press.
11	14	7	7	Atmos.
12	24	12	10	70°C. atmos.

Haddington Island andesite treated with eosin dye solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
13	24	2	2
14	48	3	3
15	48	2	3
16	60	5	5
17	72	6	6

Recrystallized Grenville limestone from Calabogie, Renfrew county, Ontario, treated with eosin dye solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
18	48	3	3
19	72	4	4
20	168	5	5

Recrystallized Grenville limestone from Calabogie, Renfrew county, Ontario, treated with eosin dye solution at a temperature of 115 degrees Centigrade and 1268 mm. pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
21	3	4	4
22	2	3	3
23	$1\frac{1}{2}$	3	3

Haddington Island andesite treated with sodium sulphide solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
24	48	3	3
25	84	4	4
26	168	6	6

In these experiments the sodium sulphide turns the rock black after being in contact with it a few hours. When the rock specimens were broken open this dark coloration had advanced into the rock the distances shown in the above table, but the centre of the rock was not yet discolored.

Haddington Island andesite treated with ferric chloride solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
27	48	4	4
28	168	4	4

Oriskany sandstone from Oneida township, Ontario, treated with eosin dye solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
29	24	4	5

Magnesian limestone from Oneida township, Ontario, treated with eosin dye solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
30	24	3	4
31	70	4	5

Magnesian limestone from Oneida township, Ontario, treated with cupric sulphate solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
32	24	2	2
33	60	3	3

Coarse-grained, Grenville, recrystallized limestone from Renfrew county, Ontario, treated with eosin dye solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
34	70	2	2

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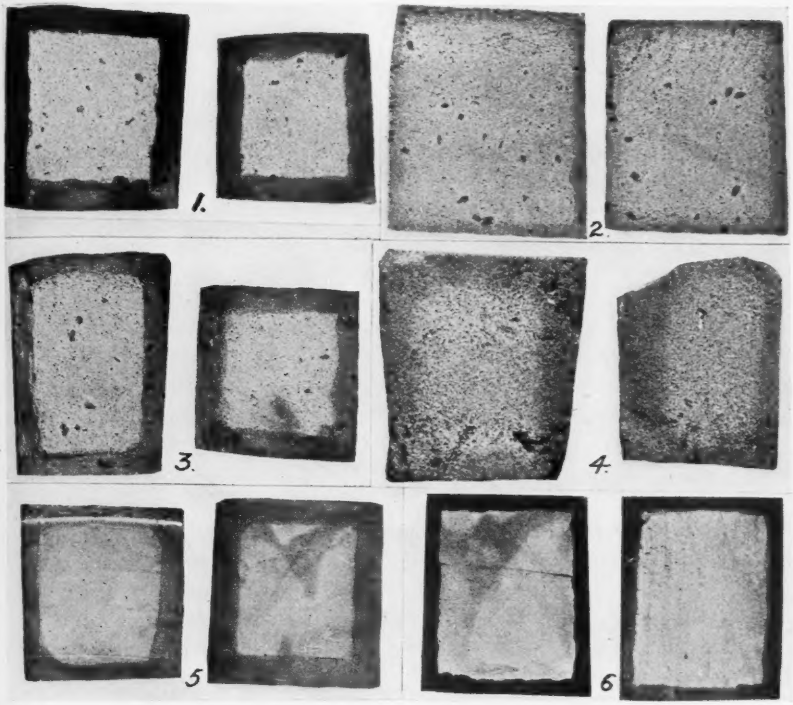

FIG. 1. Approximately equal penetration of cupric sulphate solution into saturated and unsaturated specimens of Haddington Island andesite; 48-hours (natural size).

FIG. 2. Same, with eosin dye solution.

FIG. 3. Same, with ferric chloride.

FIG. 4. Equal penetration of eosin dye solution into saturated and unsaturated specimens of sandstone from Oneida township, Ontario; 24-hours (natural size).

FIG. 5. Same, with eosin dye solution into limestone from Oneida township, Ontario.

FIG. 6. Same, with cupric sulphate into Oneida limestone; 60 hours.

Coarse-grained, Grenville, recrystallized limestone from Renfrew county, Ontario, treated with eosin dye solution at atmospheric temperature and pressure.

No.	Time in hrs.	Sat. Spec. Pen. in mm.	Unsat. Spec. Pen. in mm.
35	70	1	1

Discussion of Results.

The results of the experiments show no very great difference between the penetration of a solution into saturated and unsaturated rocks; in fact, in many cases the penetration is identical. It might be expected that penetration into the unsaturated rock, that is, by capillarity would be considerably greater, but this does not seem to be the case. This similarity in penetration was brought out forcibly in the experiments with andesite from Haddington Island, and the limestone from Oneida township, Ontario, when penetrated by ferric chloride or cupric sulphate. The same phenomenon was shown in the case of Grenville limestone from Renfrew county, Ontario, when treated with cupric sulphate or eosin dye solution.

In both the saturated and unsaturated specimens there is indicated slightly faster penetration at first. This result might be expected in the dry rock and to some extent in the saturated specimen owing to decrease in concentration of the solution because of dilution by the water in the rock. After the solution had been standing some time with the specimen immersed in it some of the solute precipitated on the surface of the rock. The lowering of the concentration of the solute by precipitation would tend to lower the ability of the solute to diffuse into the rock.

Experiments were performed to determine whether a difference in the concentration of the penetrating solution would make a difference in the degree of penetration. Two solutions of cupric sulphate were prepared, one containing 6 grams of cupric sulphate per 100 c.c. of water and one containing 3 grams of cupric sulphate per 100 c.c. of water. Dry specimens of Haddington Island andesite were immersed in each solution for eighteen hours. At the end of that time the blocks were broken open and the penetra-

tion determined. The results showed that the stronger solution had penetrated a distance of 4 mm. and the weaker only 3 mm. A similar experiment was carried out with saturated specimens of andesite. The stronger solution in this case showed a penetration of 3 mm. and the weaker slightly over 2 mm. These results seem to indicate that the concentration of the solutions entering the rocks is a factor affecting the rate of entry.

As well as showing the similarity in rate of entry by capillarity and by diffusion, the experiments brought out another interesting feature. In every case of penetration into unsaturated rocks there was a separation between the various parts of the solution. Every case showed that although the whole rock was saturated with solution, the metal of the salt contained in the penetrating solution had only penetrated a short distance. This separation occurred with all solutions and all rocks used in the experiments. To illustrate this point consider experiment No. 4 in the list. A block of andesite was immersed in a solution of cupric sulphate for forty-eight hours. When the block was broken open it was completely saturated with solvent, but when dipped in sodium sulphide, the black coloration, showing the presence of copper, extended in only 5 mm. This indicates there had been a separation between the solute and solvent parts of the solution, and that the solvent penetrates the rock ahead of the solute.

The cause of this separation may be one of several but it seems that the rock allows an easier penetration of the solvent than the solute. That is, the rock acts as an imperfect semipermeable membrane. Lindgren [4] says that undoubtedly porous rocks act as a semipermeable membrane through which various substances will diffuse at differing rates.

Adsorption may be a cause of the separation, and reaction of the solution with minerals of the rock may precipitate the base of the salt and allow the remainder of the solution to penetrate farther into the rock.

It has long been known that filtering water through sand will purify it. Berzelius filtered solutions of common salt through

[4] Lindgren, W.: Mineral deposits, p. 196, McGraw-Hill Co., New York, 1928.

sand and found the first portions of the filtrate to be fresh, and Matteucci [5] obtained similar results with other salts.

Water hydrolyses the salts of weak acids or bases, with the base usually remaining as a very fine colloid. Where this process occurs there will certainly be a separation between the various parts of the solution because colloids do not penetrate rocks along capillary openings to any great extent.

Where base exchange between the solution and minerals of the rock occurs, naturally a separation will take place in the solution. The base of the salt in solution will be left behind, while the rest of the solution penetrates the rock. Where salt solutions, capable of reaction with the rock minerals, penetrate rock masses, base exchange is probably an important factor in the separation. Splitting of the salt into an acid portion and basic portion, with different rates of mobility, as well as adsorption, may cause some separation; but chemical reaction of the salt with the rock seems the most likely cause.

The separation of the solution gives an explanation of the apparent similarity of penetration of salts in solution into saturated and unsaturated rocks, in other words the similarity in penetration by capillarity and by diffusion. Regardless of the exact manner in which this separation occurs, it does take place, hence any further movement of the solute must take place through a block that is saturated.

The experiments show that porosity and permeability are factors that affect the rate of separation taking place in the solution and the rate of entry into the rock. The more permeable rocks show a greater penetration both in the case of the saturated and unsaturated specimens than do the less permeable ones over a similar period of time.

Experiments with the recrystallized limestone from Calabogie, Ontario, carried out in a bomb at a temperature of 115 degrees Centigrade showed the same equal penetration of dye into the saturated and unsaturated specimens. The rate of penetration in

[5] Matteucci: Sur les Phenomenes Physique de Corps Vivants, p. 29, Paris, 1847. Cited by Sullivan, E. C.: U. S. Geol. Surv. Bull. 312, p. 7, 1907.

these experiments however was considerably faster, there being a penetration of 4 mm. over a three-hour period.

EXPERIMENTS WITH COLLOIDAL SOLUTIONS AND VARIOUS ROCK TYPES.

Experiments similar to those described, with dilute colloidal solutions, and the various rock types used in the experiments with true solutions.

The solutions used in the experiments are as follows:

(1) Colloidal solution of ferric hydroxide $Fe(OH)_3$.
(2) Colloidal solution of the oxide of molybdenum Mo_3O_8.
(3) Colloidal solution of ferric ferrocyanide $Fe_4[Fe(CN)_6]_3$.
(4) Colloidal solution of manganese dioxide MnO_2.
(5) Colloidal solution of silicic acid.

The majority of the solutions mentioned above have a distinct color and leave a definite mark wherever the colloidal particles enter the rock.

Rock	Colloid	Time in hrs.	Penetration
Andesite	$Fe(OH)_3$	72 hrs.	Less than .5 mm.
Andesite	Mo_3O_8	240 hrs.	nil.
Limestone from Oneida Tp., Ont.	$Fe_4Fe(CN)_{6\,3}$	50 hrs.	nil.
Limestone from Oneida Tp., Ont.	MnO_2	50 hrs.	nil.
Limestone from Oneida Tp., Ont.	$Fe(OH)_3$	50 hrs.	nil.
Cataract sandstone	$Fe(OH)_3$	72 hrs.	nil.
Cataract sandstone	$Fe(OH)_3$	48 hrs.	nil.
Cataract sandstone	$Fe_4Fe(CN)_{6\,3}$	50 hrs.	nil.
Sandstone from Oneida Tp., Ont.	$Fe_4Fe(CN)_{6\,3}$	50 hrs.	2 mm.
Coarse-grained marble	$Fe(OH)_3$	72 hrs.	nil.
Coarse-grained marble	Mo_3O_8	240 hrs.	nil.
Coarse-grained marble	MnO_2	50 hrs.	nil.

DISCUSSION OF RESULTS.

The results bear out the theoretical conclusion that colloids have no very great power to penetrate rocks along capillary openings. The unstable nature of colloids in general, and the tendency for them to be precipitated by contact with an electrolyte makes them not specially adaptable for penetration into rocks. The one case in which any appreciable penetration did take place was in a rock in which the pores were very large and numerous. Therefore the size of the pores has an effect on the penetration.

Experiments were tried in which colloidal solutions of ferric hydroxide and molybdenum blue were passed through tubes tightly packed with sand. These tubes were connected with an open tube into which the solutions were poured. The solutions could then migrate upwards through the sand grains by means of capillarity and a slight hydrostatic pressure. The separation of the continuous phase from the colloidal particles was immediate. The continuous phase rose fairly rapidly through the sand, but the colloidal particles were coagulated near the lower end of the tube and rose only very slowly.

In all the experiments with colloidal solutions and rocks, the specimens upon being broken open had been penetrated by the continuous phase, but not by the dispersed phase. The cause of the separation in this case is more obvious than in the case of the true solutions. If the colloidal particles are smaller than the capillary openings, a certain amount of penetration may occur. These particles, however, would move with difficulty while the continuous phase would move with comparative ease. The dispersed phase on seeking entrance into the rock, would tend to lodge in the capillary openings and thus prevent any further migration.

CONCLUSIONS FROM EXPERIMENTS WITH TRUE SOLUTIONS.

The experiments with true solutions show that in the rocks and solutions used, there is no appreciable difference in the rate of entry of the salt in a salt solution into saturated and unsaturated rocks. When a solution enters an unsaturated rock, there occurs a separation between the basic portion and the remainder of the solution. The basic portion moves much more slowly. This separation takes place soon after penetration has begun; for even those experiments of short duration show no very great difference in the amount of penetration of the solute, though the solvent has penetrated much farther.

Several factors may be active in accomplishing the separation, namely:

(1) A difference in the rate of migration in the acidic and basic portions of the solution.

(2) Chemical reaction causing precipitation of the basic portion and allowing the remaining part of the solution to migrate farther.

(3) Adsorption may cause some degree of separation, but it is not as important as the first two mentioned processes.

(4) The rock may act as an imperfect semipermeable membrane allowing an easier passage of part of the solution.

Due to this separation in the invading solution, the solute really enters the rock by diffusion rather than by capillarity. The concentration of the penetrating solution has an effect upon the rate of entry. The porosity and permeability are also factors affecting the rate of entry. Finally in view of the results of the experiments diffusion may play a greater rôle in the migration of material through rocks than some geologists have attributed to it.

DIFFUSION IN THE PROCESSES OF ORE CONCENTRATION.

Where fractures allow the free access and migration of solutions, diffusion is not likely to be very active. If for any reason there is a stoppage of flow and conditions become stagnant, diffusion will begin to operate and aid in the movement of material in solution. As such conditions are very likely to occur as the solutions migrate through the rocks, diffusion becomes more or less an important process in the movement of material in solution.

Lindgren,[6] in speaking of the deposits of Cripple Creek, says:

> Diffusion in itself is a slow process and yet in porous rocks may well play an important rôle, especially when chemical reactions accompany it. In the latter case adsorption and metasomatism cause constantly changing conditions of saturation by which the process is made enormously concentrated.

Rôle of Diffusion in Metasomatism.

Lindgren[7] defines metasomatism as a simultaneous molecular process of solution and deposition by which in the presence of a fluid phase one mineral is changed into another of differing chemi-

[6] Lindgren, W., and Ransome, F. L.: Geology and gold deposits of Cripple Creek. U. S. Geol. Surv., Prof. Paper 54.

[7] Lindgren, W.: Metasomatism. Bull. Geol. Soc. of Amer., vol. 36, p. 247, 1925.

cal composition. The loci of this process are in the capillary and subcapillary openings in the rocks. A certain amount of replacement may take place in open spaces but the greater amount is accomplished in the minute, interstitial spaces within the solid rocks. The solutions carrying the replacing minerals penetrate these spaces and finally saturate the rock.

Whether the rock being penetrated is saturated or dry, the experiments described above show that diffusion will play a prominent rôle in the movement of solutions through the rocks and the salts dissolved in the solutions. In the main channels such as fractures, there will probably be considerable movement, but in the capillary and subcapillary spaces, movement is very slow or practically absent. Here are ideal conditions for the process of diffusion. The replacing solution attacks a rock grain, dissolves one mineral and deposits another in its place. This process results in a lowering of the concentration of the replacing mineral at the point of replacement. Due to this lowering of concentration, diffusion will cause a movement of molecules of the replacing substance to the point of replacement. At the same time the substance taken into solution will have a higher concentration at the point of replacement, and diffusion will tend to move it out to the main channel of migration where it will be carried away.

Lindgren says that diffusion is incompetent to originate mineral deposits of a primary nature. It must be supplemented by movement of solutions along open fractures or other spaces. He agrees, however, that in metasomatism diffusion plays its most important rôle; thus, since a great many deposits are formed by the process of metasomatism, diffusion may become important in the formation of primary ore deposits.

Rôle of Diffusion in the Formation of Primary Ore Deposits.

It is generally accepted that the carriers of minerals found in ore deposits are hot aqueous solutions that are derived as an end product of the crystallization of a parent magma. These solutions with their content of dissolved minerals leave the magma under

an inherent pressure and will migrate through the rocks, first along fractures, the channels of least resistance. In this migration, diffusion will play little if any part. Finally these solutions, finding their passage more difficult will force their way into the capillary and subcapillary openings, between the constituent grains of the invaded rock. Migration is not very easily accomplished where mineral-bearing solutions are proceeding along capillary and subcapillary openings in rocks that are buried to a depth of several thousand feet. Soon there is a separation in the various parts of the solution with the solvent moving ahead. After this separation has taken place, diffusion will be an active process in the movement of material as was indicated in the experiments.

The walls of veins commonly show alteration which extends into the country rock for various distances. In such cases diffusion will have played no very important part in the actual movement of the material along the fractures but it plays an important part in the metasomatic action by which the walls of the vein are altered.

Another case where diffusion probably acts in the distribution of material, is where a solution migrating upwards comes in contact with an impervious layer. Many examples are known of ore deposits being found underneath impervious barriers. When the solution comes in contact with such a barrier conditions will become stagnant and movement of solutions will be very slight. In such cases it seems likely that diffusion will act to a considerable extent, moving material from one place to another.

Rôle of Diffusion in Secondary Enrichment.

The waters travelling downward in the zone of oxidation migrate chiefly along the fractures but also penetrate the rock masses along capillary openings. Movement in these capillary openings is very slow. By travelling along these minute openings between the various rock grains, the solutions are able to dissolve mineral grains. Then in the vicinity of these mineral grains the solution in the capillary openings becomes saturated with the materials taken into solution. Diffusion then acts in moving the dissolved

substances to places of lower concentration, that is, outward to the main channels of migration. The material is then carried down to the ground-water level.

Below the ground-water table, diffusion may act in the distribution of material. Where the ground water is more or less stagnant, an influx of a substance in solution at any point would cause an increase in the concentration at the point of influx. Diffusion would then act in moving the material to places of lower concentration.

CASUMMIT LAKE, ONTARIO,
April 16, 1937.

TURQUOISE DEPOSITS OF COURTLAND, ARIZONA.

WM. P. CRAWFORD AND FRANK JOHNSON.

ABSTRACT.

Turquoise of gem quality occurs at Courtland, southeastern Cochise County, Arizona, in Upper Cambrian Bolsa quartzite and in granite of post-Cretaceous age. The turquoise has been deposited from solution in fracture zones caused by normal faulting prior to a period of thrust faulting. Its origin is genetically related to the granite. Limonite, kaolin, and sericite are associated minerals. Turquoise is found through a vertical range of 180 feet and is mined through shallow shafts, open cuts, and adits. The rough stone is sold to dealers and Indian traders.

TURQUOISE is one of the oldest gem stones of which there is record. Highly regarded by the Egyptians, turquoise ornaments have been found in graves antedating the first dynasty. The oldest mining on a large scale of which there is adequate record was for turquoise at Wadi Maghara and Serabit El Khadem on the Sinai Peninsula, these mines being worked as early as 3400 B.C.[1] The Persian turquoise mines near Nishapur have been worked for more than 800 years. In America[2]—"The American Indians worked turquoise mines in our own Southwest at a number of places before the Spanish arrived. That some of these considerably antedate the discovery of America is shown by the many thousands of turquoise beads and pendants found in Pueblo Bonito, dating from about 900 to 1100 A.D. Antedating the last at least 1,000 years are the turquoise pendants from the late Basket Makers village in Chaco Canyon, New Mexico. The turquoise mines at *Turquoise Mountain,* Cochise County, Arizona; at Los Cerillos, and in the Burro Mountains, New Mexico, were worked in pre-Columbian time and other ancient turquoise deposits are known."

[1] Ball, S. H.: Eng. and Min. Jour., pp. 483–485, 1927.

[2] Ball, S. H.: Historical notes on gem mining. ECON. GEOL., vol. 26, pp. 727–728, 1931.

Throughout the southwestern United States, turquoise is a popular gem stone, the largest purchasers being traders dealing with the Navajo Indians, by whom the turquoise is highly es-

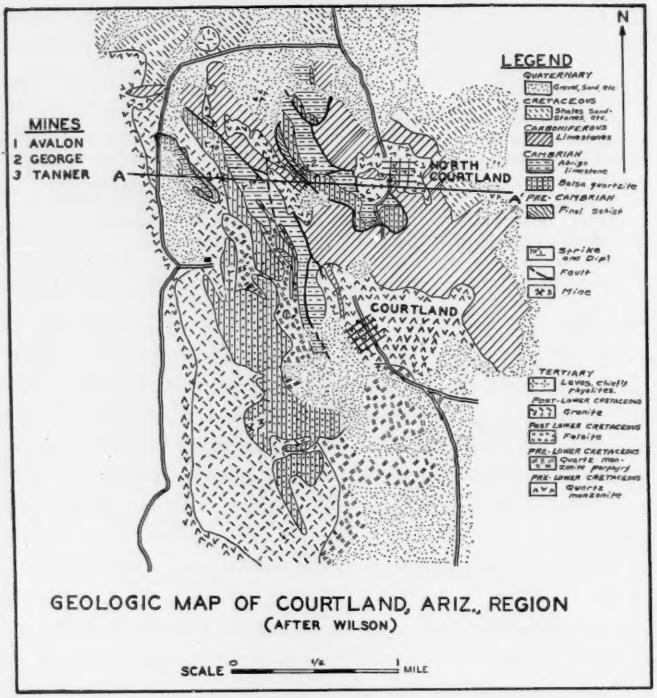

FIG. 1. Geologic map of Courtland, Arizona, region (after Wilson).

teemed. Fine turquoise for the Indian trade commands a high price and stone possessing a permanent color and an exceptional hardness is eagerly sought. The "tourist" trade provides an outlet for much second grade turquoise and "trash" that is often skillfully colored or "waxed" by the cutters; the color often fading or changing on wearing. The use of this inferior material has had an adverse effect on the turquoise trade. Although tur-

quoise matrix is now in wide favor, a clear, blue, hard turquoise remains the standard of quality and stone of this grade is increasingly hard to obtain. The deposits at Courtland, Arizona, which produce much clear, blue turquoise are of increasing importance.

The turquoise mines at Courtland (Turquoise Mountain) are situated in the Turquoise Mining District, near the old mining camp of Courtland, Cochise County, Arizona, about 20 miles north of Bisbee. The principal deposits are on the western flank of Turquoise Ridge about three quarters of a mile west of Courtland (Fig. 1). Several studies of the geology and ore deposits [3] of the Turquoise Mining District have been published, the most complete of which is that of E. D. Wilson. They deal primarily with the copper and lead-zinc deposits and mention the turquoise deposits briefly, if at all.

Ancient workings on the west side of Turquoise Ridge and antique stone implements are evidence that the deposits were known and worked by the Indians. Although W. P. Blake, in 1883, mentioned the occurrence of green turquoise at Turquoise Mountain there is no record of the gem stone being mined by whites until the nineties, when mining claims were located near the north end of Turquoise Ridge by Messrs. Raskum and Tannenbaum who operated the property intermittently until about 1903, when it was sold to George S. Goode. Goode worked the Avalon deposit until 1912, mining considerable turquoise, most of which was cut and polished in a small grinding shop at the mine. Mining operations ceased in 1912 and the claims were re-located in 1915 by L. D. Shattuck and an associate. Shattuck obtained the other half interest through purchase and has worked the property since 1926. Besides the Avalon group, other claims on Turquoise Ridge and near North Courtland have been the source of considerable turquoise. There are no available figures on the total amount nor value of the turquoise produced at Court-

[3] Ransome, F. L.: The turquoise copper mining district. U. S. Geol. Surv. Bull. 530, pp. 125–134, 1913. Platt, J. M.: The turquoise mining district, Eng. and Min. Jour., vol. 87, p. 213, 1909. Wilson, E. D.: Geology and ore deposits of the Courtland-Gleeson region, Arizona. Ariz. Bur. of Mines Bull. 125, 1927.

land, but several thousand pounds of the gem stone have been mined.

ASSOCIATED ROCKS.

The geologic formations of the Courtland region, described by Wilson, Darton, and Ransome [4] range in age from pre-Cambrian to Quaternary, and sedimentary, metamorphic rocks, igneous intrusives, and lava flows are all present. The rocks that contain the turquoise deposits are a quartzite of Upper Cambrian age and a granite of post-Cretaceous age.

Quartzite.—The only sedimentary rock related to the turquoise deposits is the quartzite, that is undoubtedly equivalent to the Upper Cambrian Bolsa quartzite of Bisbee. It is a hard, medium to fine grained, occasionally pebbly formation, massive to distinctly stratified, which presents a white to brownish-gray fresh fracture and weathers a rusty brown with local dark streaks and blotches. "Limonite," sericite, and kaolin are common impurities. The texture of the quartzite has no apparent effect on the mineralization, as both coarse and fine grained beds contain turquoise veinlets. It makes up the crest and most of the eastern side of Turquoise Ridge, an irregular thickness of it resting, with steep eastward dip, upon the surface of intrusions of post-Carboniferous granite and quartz monzonite-porphyry. To the west of North Courtland, the Bolsa quartzite has been thrust-faulted, together with Abrigo limestone and a thin wedge of Pinal schist, over Carboniferous limestone and extends northwest along the crest of a low ridge. The turquoise on the George claim occurs in this fault block. A faulted block of Bolsa quartzite, Abrigo limestone, and Cretaceous sediments lies to the west of Turquoise Ridge but no turquoise has been found in this block.

Granite.—The granite associated with the turquoise deposits is intrusive into the Bolsa quartzite and younger formations and outcrops in several dikes, and as an irregular belt on the west side of Turquoise Ridge. Hand specimens of the rock are light-yel-

[4] Wilson, E. D.: *Op. cit.*, pp. 17–26. Darton, N. H.: A resumé of Arizona geology. Ariz. Bur. of Mines Bull. 119, Geol. Ser. 3, pp. 293–296, 1925. Ransome, F. L.: *Op. cit.*, pp. 124–134.

low to nearly white in color, have medium-fine granitic texture and show considerable quartz. In thin section, the rock is highly altered and consists of quartz, orthoclase and microcline, with apatite and zircon as accessory minerals. Sericite and kaolin have formed through alteration of the feldspars. Turquoise of inferior quality is found in the granite near its contact with the Bolsa quartzite.

STRUCTURE.

The geologic structure of the Courtland region has been considerably modified by normal and thrust faulting (Fig. 2). The

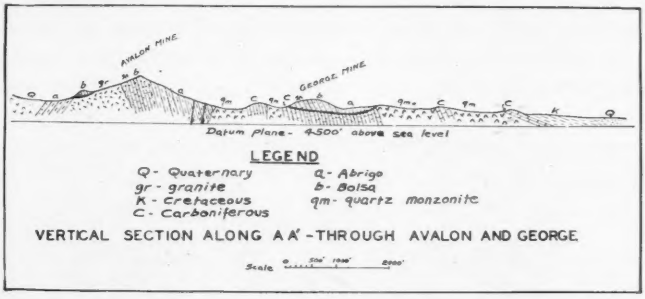

FIG. 2. Vertical section along *A A'*—through Avalon and George mines.

faulting that directly affects the turquoise deposits is ascribed to the periods of block-tilting of post-Cretaceous age and of thrust faulting of late Tertiary age. The first tilted the rocks of Turquoise Ridge to the east and created the fractures in which the turquoise was later deposited. The thrust faulting of the second period, younger than the turquoise deposition, overthrust a mass of Pinal schist, turquoise-bearing Bolsa quartzite, and Abrigo limestone over Carboniferous limestone, to the west of North Courtland. Normal faults of small throw are exposed in the Avalon workings on Turquoise Ridge and displace the turquoise veins.

TURQUOISE DEPOSITS.

Geologic literature contains numerous references pertaining to the occurrence and origin of turquoise. J. E. Pogue[5] distinguishes three types of occurrence, the Courtland deposits being representative of the second type—"the turquoise occurs in sedimentary or metamorphic rocks, near the contact with igneous rocks, with which it is apparently connected in genesis." In all three types, the most commonly associated minerals are kaolin, sericite, and hydrous iron oxide.

Properties of Turquoise.—Turquoise is a hydrous phosphate of aluminum and copper of which the formula is $CuO.3Al_2O_3.2P_2O_5.9H_2O$. The constituent percentages in turquoise from different localities vary and iron, probably in the form of hydrous iron oxide, is always present as an impurity and exerts a modifying influence upon the shade. According to Zalinsky,[6] the amount of copper affects the color and hardness of turquoise; the correct proportion of copper gives material of finer color and of greater hardness than that in which copper is deficient. An excess of copper gives the material a green color; a deficiency of copper gives it a pale color, an inferior hardness, and apparently it grades into simple phosphate of aluminum. The presence of silica also affects the hardness and possibly the color of the gem stone. An analysis of hard, clear turquoise, dark blue in color and showing no silica inclusions in polished section, from the Shattuck Tunnel at Courtland yielded: 4.48 per cent. copper, 34.00 per cent. alumina, 29.22 per cent. phosphorus pentoxide, 3.80 per cent. silica, and 1.00 per cent. iron. Water was not determined. Whether depth is an important factor in the genesis or formation of ideal turquoise is not easily determined but a study of the different deposits shows that fine turquoise seldom occurs plentifully at depths greater than two hundred feet. A little turquoise associated with malachite and chrysocolla was developed at a depth of

[5] Pogue, J. E.: The turquoise; a study of its history, mineralogy, geology, ethnology, archeology, mythology, folklore, and technology. Nat. Acad. of Sci., 3d. Mem., vol. 12, pt. 2, 1915.

[6] Zalinsky, Edward: Turquoise in the Burro Mts., New Mex. ECON. GEOL., vol. 2, pp. 464–492, 1907.

410 feet in the Copper King mine, Burro Mts., New Mexico, but the best turquoise in the Elisabeth pocket was found at depths of 100 feet or less. Turquoise is found through a vertical range of about 180 feet at Courtland. The deepest exposure of good quality turquoise is at the Goode open cut, where veinlets of turquoise are exposed in the bottom of a 60 foot shaft, and patches of turquoise are shown on the surface about 120 feet vertically above the shaft collar.

Origin.—Several papers on the origin [7] of turquoise have been published but lack of space prohibits a discussion of the various theories. The close association of kaolin and sericite with turquoise in all of the important deposits is probably more than a coincidence and the origin of these secondary minerals is possibly related to that of turquoise. In at least three deposits: Burro Mts., N. M., Courtland, Arizona, and Mineral Park, Arizona, much of the best turquoise occurs as nuggets or concretions embedded in kaolin and sericite. Sterrett [8] found turquoise at Mineral Park, Mohave County, Arizona, which was apparently formed directly from kaolin by the addition of phosphate and copper. Specimens exhibited a gradation from good turquoise to soft, semi-turquoise and to copper-stained kaolin. The field evidence so far assembled on the Courtland deposits indicates that the turquoise was deposited in the quartzite and granite prior to the period of thrust-faulting and the origin is evidently genetically related to the granite, the phosphoric acid being derived from decomposition of the apatite and the alumina from the feldspars. The small amount of copper may have been in the host rock or may have migrated from another source. Turquoise was deposited in joints and fissures in the quartzite probably from solution, and replacement of quartzite by turquoise is shown in thin sections.

[7] Zalinsky, Edward: *Op. cit.* Pogue, J. E.: *Op. cit.* Paige, Sidney: The origin of turquoise in the Burro Mts., New Mexico. ECON. GEOL., vol. 7, pp. 388–391, 1912.

[8] Sterrett, D. B.: U. S. Min. Res., Precious Stones, Pt. 2, p. 848, 1908.

AVALON GROUP OF MINES.

The Avalon group, owned by L. D. Shattuck, of Courtland, Arizona, and consisting, in part, of the Avalon Azul, and Nightingale claims, is on the western flank of Turquoise Ridge, between Leadville Gulch and the northern end of the ridge. It is the largest producer of turquoise in the district and has been worked since the nineties when the claims were located by Messrs. Raskum and Tannenbaum. Shallow pits and antique stone implements afford evidence that the deposit was known and worked by Indians, probably in pre-Columbian time. A record of the total weight and value of the turquoise produced from this group is not available, but, since 1926, about seven hundred pounds of turquoise valued at seven thousand dollars have been mined by the owner and an additional amount has been mined by lessees. The total production is probably in excess of $25,000.00.

The mine is developed by a number of open cuts, shallow shafts, and adits, with considerable underground stoping. The principal workings are the Goode workings on the Avalon and Azul claims, the Shattuck Tunnel on the Azul claims, and the Tanner Tunnel on the Nightingale claim.

Individual Workings.

Goode Workings.—The Goode workings consist of an open cut, short adits and a shaft at the south end of the Avalon claim, and a shaft at the north end of the Azul claim. The open cut, about 80 feet long, 40 feet wide and 30 feet deep, cuts across the contact of the granite and quartzite. A vertical fault, striking eastward, passes through the center of the cut. The fault outcrop has been traced across the crest of Turquoise Ridge and small patches of good turquoise are exposed. No turquoise has been found to the north of this fault zone. An adit driven eastward on the south side of the fault disclosed turquoise and considerable stoping was done. A shaft, about 60 feet deep, was sunk below the bottom of the open cut and a turquoise-bearing seam was stoped to the surface. Turquoise veinlets are visible in the bottom of this shaft and gem stone mined here in 1934

had a good color and hardness. The dump contains turquoise and is being reworked, yielding some fine quality stone. Geo. S. Goode mined considerable turquoise in a shaft at the north end of the Azul claim, about 500 feet south of the Goode cut, and some good matrix was mined here in 1926.

Shattuck Workings.—The Shattuck workings, at the south end of the Azul claim, consist of a crosscut adit several hundred feet long, with lateral drifts on favorable fractured zones, and shallow shafts and drifts. Several of the fractured zones cut by the Shattuck Tunnel have been stoped to the surface, a distance of from 60 to 70 feet, and much of the turquoise was of good quality. No work has been done below the adit level. Part of the dump at the Shattuck Tunnel was reworked in 1935 and good turquoise was mined in a shallow shaft and pit, near the crest of the ridge, in 1934.

Tanner Workings.—Two short adits and an open stope comprise the Tanner workings at the north end of the Nightingale claim. The upper adit was driven by J. B. Tanner, lessee, on a fractured zone striking northward. The turquoise vein ended against a vertical fault striking eastward and considerable gem stone was mined. L. D. Shattuck mined turquoise on a fracture east of the Tanner Tunnel and thin seams and patches of turquoise are still visible. An adit, about 30 feet below the Tanner Tunnel, was begun in 1934 to prospect for a downward extension of the turquoise, and in January, 1935, the face of the adit was in a zone of cross-fracturing containing small nuggets of hard, green turquoise.

Geologic Occurrence.

Turquoise occurs in the quartzite, principally in fractured zones having a general northward trend and dipping 70° east, and at the intersection of these fractures with those of younger age, striking eastward and dipping at high angles to the south. Turquoise occurring in the east fractures, away from their intersections with the older system of fractures, is generally a greenish color and broken. The mineralized fractures are from a frac-

tion of an inch to several inches in width and occur in both single and compound zones. Turquoise occurs in these zones as stringers, nodules, and nugget-like masses; the nuggets commonly being in the softer portions of the veins and embedded in sericite and kaolin and usually make the finest gems. Sericite and kaolin are commonly associated with the turquoise, separating it from the quartzite walls. The turquoise is from one sixteenth to one and one half inches in thickness, most of it, however, being from one eighth to one-half inch thick. "Limonite" is a common accessory mineral, malachite is rare and variscite has not been observed. Kaolinized and sericitized material, stained green to blue, occurs in large masses and resembles turquoise, when damp, but is soft and the color fades on drying. This clayey material is probably identical with Sterrett's semi-turquoise and might, under favorable conditions become turquoise, as at Mineral Park, Arizona.

Joints in the quartzite away from the main fractured zones are filled with veinlets of turquoise, generally unassociated with kaolin or sericite. The examination of thin sections of this material often shows a partial to complete replacement of the quartzite grains by turquoise. The color and hardness of this turquoise are usually excellent and some of the finest gem material is obtained through cobbing the thicker veinlets. Both clear and matrix turquoise are obtained and in the matrix the most common impurity is a limonite-stained quartzite that takes an excellent polish.

Mining and Marketing.

The best turquoise mined from the Avalon property is comparable to the finest turquoise from either the Cerillos Hills or the Elisabeth pocket of the Azure mine, Burro Mts., New Mexico. It is light to dark-blue in color, very fine grained, translucent, and slightly above six in hardness. The color is permanent, unaffected by grease or sunlight, and the stone takes a brilliant polish. The largest single mass of high grade turquoise found since the mines were reopened in 1926 was taken

from a stope above the Shattuck Tunnel and was a mass of clear, dark blue stone, above six in hardness, and weighing one pound and six ounces. Pieces weighing about one ounce are commonly found.

The lower grade turquoise is slightly softer than the best turquoise and some of it is coarse grained or porous. In color, it varies from green through shades of blue to dark blue and although most of it retains its color permanently some of the porous stone darkens and becomes greenish.

The turquoise matrix varies in color from green to dark-blue and the impurities are kaolin, sericite and quartzite, both clear and limonite-stained. Quartzite is the most desirable impurity as it makes a better pattern, and takes a good polish. Kaolin or sericite usually tear out or pit during cutting and are quickly discolored.

Mining methods are simple. Turquoise exposed on the surface is mined in pits and open cuts. Adits are driven in the quartzite to prospect for mineralized fractures and the turquoise is mined by overhand and underhand stoping. Drill holes shot in the soft seams shatter and break the turquoise and to avoid loss of the gem stone, holes are drilled in the quartzite which increases the powder cost but reduces the amount of shattered turquoise. Broken rock is sorted underground and dumped on the surface, where it may be sorted a second time. Quartzite containing thick seams of turquoise is cobbed.

The turquoise is sorted into two grades. It is washed to remove dirt and the soft, inferior stone and waste are rejected. About five per cent. of the finest turquoise is picked out as the No. 1 grade and the remainder is classed as mine-run or No. 2 turquoise. In 1929, the No. 1 grade sold for $50.00 a pound, uncut, and the No. 2 grade for $10.00 a pound. In 1934 and 1935, the No. 1 grade commanded from $25.00 to $40.00 a pound and the No. 2 grade from $5.00 to $10.00 a pound, depending upon the size, color, and hardness. The price is higher for large specimens, an offer of $300.00 for a specimen weighing one pound and six ounces being refused.

The Avalon turquoise is well known among Indian traders in Arizona and New Mexico and the entire output is sold to dealers in Gallup, New Mexico.

OTHER PROPERTIES.

George Claim.—The George claim, located by Tannenbaum and George and now owned by John Gleeson, is about one-half mile west of North Courtland in an over-thrust block of Bolsa quartzite. The turquoise was mined in a narrow open cut and a short adit, and in shallow surface pits. It is in fractured quartzite associated with kaolin and sericite. Steep faults with small throw are exposed in the open cut.

Considerable high grade turquoise was taken from the claim by the former owners and, in 1931, J. B. Tanner mined a quantity of fine turquoise from a shallow trench near the top of the old open cut and also recovered considerable gem material by washing and reworking the old dump. In 1932, a small amount of turquoise, thin and a poor color, was mined from this claim and surface prospecting in 1935 exposed thin veinlets of high grade stone.

Tanner Claim.—The Tanner claims, owned by J. B. Tanner, of Farmington, New Mexico, are on the west side and near the south end of Turquoise Ridge. The claims were originally located by Raskum, who mined turquoise from them in the nineties. Ancient pits and stone implements show that the Indians worked this deposit.

The turquoise is found in the granite and the color varies from a light to dark-green. Much of it is soft, but some is sufficiently hard to take a good polish. The best turquoise is found at the surface and to a depth of 20 feet. Below that depth it is mostly of poor color and low hardness. Blue turquoise is seldom found. The claims are not being worked as there is little demand for green turquoise.

Recent Development.—Exposures of minable grade turquoise were worked during 1936 and considerable high grade stone was recovered. The blocked out reserves are small as the deposits are

worked by gouging and little development work is done in advance of mining. The Avalon dumps contain available gem material and green turquoise is present in considerable quantity on the Tanner claims. Proposed exploration of the quartzite south of Leadville Gulch may develop additional blue turquoise and detailed geologic mapping of the turquoise area should prove of value as several favorable blocks are unprospected.

BISBEE, ARIZONA,
Feb. 26, 1937.

REVIEWS

La Geologie et les Mines des Vieilles Plateformes. By F. BLONDEL. Publication du Bureau d'Etudes Geologiques et Minieres Coloniales, Paris, 1936.

F. Blondel, Ingeneur en chef des Mines of the above-named bureau, has undertaken an appraisal of the possible mineral resources of the French colonies, two thirds of which lie in the kind of region discussed. The book results from a series of lectures given in 1934–1935 at the National Museum of Natural History in Paris. As a preparation, he has reviewed the mineral resources of similar regions throughout the world to establish, as far as possible, what resources we may expect to find or not to find in such regions.

The author uses the term "vieilles plateformes" for those stabilized masses known as shields, although that term has been seriously misused in this country and should, from the structural point of view, include, as it does in Blondel's usage, not only the area of the exposed fundamental rocks but the region overlain by a cover of younger horizontal sediments or volcanics,[1] which Blondel calls "serie de couverture." The underlying rocks he subdivides further, for the purpose of his analysis, into the crystalline basement ("socle crystalline") and "serie semi-metamorphique." The basement rocks are characterized by the presence of gneisses; the semi-metamorphic series by more or less schistose rocks separated by a great unconformity from the underlying crystallines and, commonly, by a marked unconformity from the "serie de couverture."

Blondel also calls attention to, and discusses at some length, those strips of folded, relatively young rocks that occur within the "serie de couverture"; in particular he takes up the Arbuckle-Wichita belt of the United States and the Northern Rhodesia-Katanga belt of Africa. (To these might be added the MacDonnell Range of Australia and the Rio Sao Francisco region of Brazil.) These belts he refers to as "sillons intracontinentaux" which might be translated freely as intracontinental troughs.

Blondel's separation of these troughs from true geosynclines seems to the reviewer to be based primarily on the localization of the latter between

[1] Sampson, Edward: Mineral commerce and international relations; Jour. Franklin Inst., vol. 221, no. 1, pp. 1–58, 1936.

platform areas, and he regards the Tethys region and the Alpine conditions in particular as representative of true geosynclines. The troughs he further characterizes as not containing abundant metamorphic rocks and not showing great overthrusting comparable to the Alps. Also they have become rigid after a single period of diastrophism and have "neither a past nor a future.

It seems to the reviewer that Blondel has ignored the past of such a region as the Arbuckle-Wichita with its enormous thickness of sediments as compared to the corresponding rocks of the "serie de couverture" not far distant, and surely the thrusting of the region is too great to be brushed aside lightly. The idea is not discussed that shield areas may have grown by fusion of smaller areas with the stabilization of intermediate zones after a single great period of diastrophism. Blondel is inclined to regard the Scandinavian mountains as representing an intracontinental trough with the seaward platform foundered. The sequel of this postulate would place the Appalachians in the same category of an intracontinental trough rather than a true geosyncline!

A substantial part of the book gives an excellent summary of what is known of the shield areas, with notes on the outstanding mining camps and coal and oil fields, and particularly a correlation of these resources with their broader geologic setting. This is carried to the point of giving statistics of production for the major mineral products for each of the three subdivisions (crystalline basement, semi-metamorphic series, and covering series) of the shield areas, and for the surrounding folded belts. This part of the book represents a large amount of work, and although a few errors are noted and some references have not been consulted which would have been useful, the summary as a whole is of a high order and, taken in conjunction with the statistical treatment, serves well the main purpose of the book.

Blondel offers a suggestion of genesis of such interest as to warrant special consideration, even though many geologists will find points of strong disagreement. Following his view of intracontinental troughs outlined above, he brings up for joint consideration the Mississippi Valley zinc and lead deposits, the Northern Rhodesia-Katanga copper deposits, and the gold deposits of the Rand. For the Rand deposits he accepts a hydrothermal origin. After citing the difficulties in accounting for the origin of the ores of each of these regions, he says (freely translated):

"But if each of these presents an enigma when taken alone, nobody seems to have noticed that the enigma is the same in every case—and more or less the nature of the metal (à la nature près du métal).

Before enquiring if this relation may not lead directly to the solution, we shall recall the differences that exist between the tectonic style of the three platforms in question. The American platform is the most rigid:

at the most one notes that the deposits of zinc are not very far from the trough of the Ouachita Mountains; those of lead are much farther north, on the north slope of the Ozark dome. The African in the region of the gold mines of the Transvaal is much less rigid, one recalls that it shows large undulations; finally in the region of Katanga and Rhodesia one finds so little rigidity that one asks oneself if it was suitable to leave it in the old platform.

But the classification by the order of increasing rigidity; copper (Katanga); gold (Transvaal); zinc and lead (Mississippi), is it not the same order of classification that one finds in that which we call the contact deposits when the four metals are associated."

Then follows a citation from W. H. Emmons' paper on "Primary downward changes in ore deposits," after which Blondel continues:

> . . . The experience of numerous contact deposits leads to the evidence of the order copper-zinc-lead, beginning from the eruptive rock, with a slightly doubtful place for gold which is situated most often between copper and zinc. In other words, these four metals seem to possess increasing facility for migration starting from the deep source in the order which has just been indicated. Now it is exactly the order of increasing rigidity of the platforms whose covers we are concerned with at present. And it is not absurd to suppose that the more rigid a platform is, the more it opposes an obstacle to the migration of the metals. The relation between the two facts is not very difficult to imagine. . . .
>
> One can propose then, as an hypothesis, the following formula: the covers of the old platforms appear to be the place of election of the metals copper, gold, zinc, or lead, but with selection of one or the other of these metals following the tectonic style. The more rigid the region, the more one has to do with a metal which escapes easily. . . . [In conclusion, of special importance are] the petrographic nature of the original eruptive rock and the tectonic style of the region.

Many, as does the reviewer, will take exception to some of Blondel's conclusions, if not some of his premises; but the attempt to correlate magmatic and post-magmatic events with the structural history of the region is one of fundamental importance, and those who would wish to criticize Blondel's views will find themselves confronted with many facts they cannot fully explain. In the discussion of the magmatic source of the Mississippi Valley ores, the reviewer knows of no author who has considered the nature of the underlying magma chamber and the effects which might be produced by its peculiar structural history. Blondel has stepped out into dangerous ground, and experienced economic geologists who will venture there with him will give their colleagues much to think about.

In conclusion, the reviewer has emphasized perhaps disproportionally some of the most speculative features of Blondel's book. In it is a large body of sound data carefully compiled. The book is worthy of thoughtful

reading by all geologists interested in the regional distribution of mineral resources.

EDWARD SAMPSON.

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Die Federow-Methode. By W. NIKITIN. Pp. ix + 109. Figs. 41. Pl. 7. Gebrüder Borntraeger, Berlin, 1936. Price 12.40 RM.

In spite of the large number of papers describing the use of the universal stage in mineralogical investigation, it has been left for the author of the little book before us to gather up the suggestions of the various users of the appliance and present them in a consistent discussion of the value of the method proposed by Federow in 1891, and the ways in which the universal stage may be employed in determining the optical properties of crystals without the necessity of preparing specially oriented sections of them for study.

The book is divided into seven parts of which the first deals with the various types of the apparatus, the second with the determination of symmetry elements of a mineral fragment under observation, the third with the method of determining by total reflection the indices of refraction of a mineral exhibiting cleavage, the fourth with the determination of the magnitude and the character of the double refraction in random mineral sections, the fifth with indirect ways of determining double refraction and axial angles, the sixth with the methods of determining the position of cleavages, twinning planes, twinning axes and other crystallographic elements in crystal grains, and the seventh the use of the Federow methods in the investigation of the feldspars.

The book is well provided with explanatory diagrams and others to aid in the calculation of the values obtainable from the observations made. The discussions are clear and comprehensive and are detailed enough for all practical purposes of mineralogists and those engaged in petrofabric analyses.

W. S. BAYLEY.

Les Grandes Regions Geologiques Du Sol Francais. By PROF. LEON BERTRAND. Maps, 8; figs., 5. Ernest Flammarion, Editeur, Paris, 1936. Price, 15 Fr.

This excellent account of the geology and structural evolution of France will be appreciated by all who are interested in theoretical geology. The structural features of France, on the whole, are extremely interesting and this very successful endeavor to analyse the most important structural development of the French Alps and the Pyrénées mountains is of special

significance. The masterly treatment, in these chapters, of the tectonic implications of the Alps and Pyrénées is of extraordinary interest and of great value. Within these few pages, light is shed on many debated questions. The discussions are short and concise, but nevertheless rather easily read, considering the inherent difficulty of the problem of the Alpine orogenesis. The author has successfully interwoven the opinions of different eminent tectonic geologists of France, such as Haug, Termier, and Marcel Bertrand.

In the introduction is given a short description and explanation of the different tectonic units commonly met. Following this, Prof. Bertrand has treated the structural evolution of France from the beginning of the earth's history up to the present. The distribution of rocks in different parts of France from the early geological period, and the characteristics of their nature and form are treated chapter by chapter. This is the first attempt to gather together in one book descriptions of the geological characteristics of all the different regions of France. At the end of the book, there are a few sketch maps of the different geological units of France, such as Massif Central, the Alps, the Pyrénées, Jura Mountain, the coal basin of northern France and of the Ardenne, Massif armoricain, etc.

This is a book from which one may obtain a comprehensive idea of the geology of France without entering into the complicated details, but it is wanting in references which would have been useful for anyone desiring to pursue a more detailed study. Prof. Bertrand's French is simple and clear, and a working knowledge of French is all that is necessary to enable a person to go through this book with ease.

S. Deb.

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Congrès International des Mines, de la Métallurgie et de la Géologie Appliquée. Section de Géologie Appliquée, 2 Vols. Pp. 1088, Paris, 1936.

This highly important publication contains 126 papers presented before the Congress in Paris, in October, 1935, by authors from all over the world. They are all written in, or translated into, French. The number of outstanding papers and contributions are so numerous that it is impossible to review them and it will require months to read them—for which one will be well repaid.

Section I (231 pages), on Deposits of Igneous Origin, deals with deposits of gold, copper, pyrite, zinc, lead, vanadium, manganese, iron, diamonds, titanium, zircon, nickel, and cobalt in Europe, Quebec, Africa,

and China. Section 2 (168 pages), Deposits of Sedimentary Origin, contains 17 papers relating chiefly to coals, iron, sulphur, and sulphates. Section 3 (122 pages), Petroleum, contains 19 papers on oil occurrence, origin, stratigraphy, structure, microfossils. Section 4 contains 5 papers dealing with the application of geology to public works, and 5 papers on the application to agriculture. Section 6 has 210 pages and 26 papers on Hydrology, covering areas of Europe and Africa. Section 7 contains 10 papers under Geophysics. Section 8 has 15 papers devoted to Instruction and Research Institutes and 6 papers relating to applied geology in Mozambique.

Valuable theoretical papers are interspersed with interesting descriptive ones. The science of economic geology will profit greatly from the wealth of valuable material that is contained in these two excellent volumes.

ALAN BATEMAN.

Mineralogy, An Introduction to the Study of Minerals and Crystals. By W. F. HUNT AND L. S. RAMSDELL. 3d Edition. Pp. 638, figs. 812. McGraw Hill, New York, 1937. Price $5.00.

A thorough revision of a well known text. The additions particularly noted are: Data on X-ray analyses and interpretations of the internal structure of minerals based upon X-ray studies; on crystal structure; and the polarizing microscope. Applications of the minerals to industry have been stressed and statistics brought up to date. Some 66 illustrations have been added and there are 34 additional pages. The part relating to crystallography is clearly and lucidly presented. The descriptions of about 150 minerals are accompanied by many photographs of the minerals, their occurrence, their mode of treatment or preparation, and of eminent mineralogists. Several of the photographs of minerals, however, do not convey much. The glossary and tables are useful. The book is interestingly written and well printed.

A. M. B.

Weather Elements. By THOMAS A. BLAIR. Pp. 401; figs. 107. Prentice-Hall, New York, April, 1937. Price $4.00.

For the many people interested in weather and who desire to forecast it a few days ahead, this book by a Senior Meteorologist of the U. S. Weather Bureau will prove entertaining and valuable. The first 9 chapters deal with the physical principles underlying the behavior of the atmosphere. Another 4 chapters deal with forecasting, world weather and climate. The U. S. Weather Bureau is explained and statistical tables are appended.

BOOKS RECEIVED.

J. D. BATEMAN.

Geology and Ore Deposits of Norberg. PER GEIJER. Pp. 162, figs. 67, maps 6. Sver. Geol. Under., Stockholm, 1936. (In Swedish with English summary.) Geology and Origin of iron ores, manganiferous ores, and sulphides; skarn type; formed by metasomatic action of emanations from granite.

Gold Mining and Milling in the Black Mts., Western Mohave County, Ariz. E. D. GARDNER. Pp. 59. U. S. Bur. of Mines, I. C. 6901, 1936. Description of operations and methods.

Geology and Ore Occurrence of the Hog Heaven Mining District, Flathead County, Mont. P. J. SHENON AND A. V. TAYLOR, JR. Pp. 26, figs. 5, pls. 6. Mont. Bur. of Mines and Geol., Mem. 17, 1936. Includes interesting detailed description of a unique silver occurrence.

Soil Survey of Ohio and Switzerland Counties, Ind. B. H. HENDRICKSON, T. M. BUSHNELL, H. P. ULRICH AND D. R. KUNKEL. Pp. 60, map. U. S. Bur. of Chem. and Soils, Series 1930, No. 37. Price, 30 cts.

The Tungsten Mineralization at Silver Dyke, Nev. P. F. KERR. Pp. 70, figs. 53, maps 4. Bull. of Nev. State Bur. of Mines, vol. 30, No. 5, 1936. Price 40 cts. A well-illustrated and informative report on the scheelite-bearing zones.

Geomorphology of the North Flank of the Uinta Mts. W. H. BRADLEY. Pp. 40, pls. 11, figs. 14, map. U. S. Geol. Surv. P–P. 185–I, 1936. Price, 45 cts. A splendid dissertation on erosion surfaces resulting from local glaciation.

Geology and Gold Deposits of the Potaro. G. J. WILLIAMS, with Petrographical Appendix by D. R. GRANTHAM. Pp. 62, map. Br. Guiana Geol. Surv., 1935. Price, 72 cts., 1936. Placer gold.

Geology and Gold Deposits of the Konawaruk. S. BRACEWELL. Pp. 20, fig. Br. Guiana Geol. Surv., 1935. Price, 12 cts., 1936. Lode and placer gold; diamonds.

1934 Reports, Geological Survey of British Guiana, 1936. Pp. 76, maps 7. Price $3.00. Lode and placer gold, diamonds, lateritic ironstone, water power sites and flight reports.

Quarter-Centennial Memorial Volume of the Division of Natural Resources, Texas. Pp. 298, figs. 37, pls. 4, map. Univ. of Texas. Bull. 3501, 195.

Reconocimiento Geologico de los yacimientos petroliferos del departamento de Puno. A. C. LA ROSA AND G. PETERSEN. Pp. 100, pls. 11,

map. Cuerpo de Ingenieros De Minas Del Peru, Bol. 115, 1936. Geology of petroleum region.

Clay Resources of T. V. A. Region. (Part 1.) Pp. 32. T. V. A., Div. of Geol., Bull. 4, 1936.

Sudbury Nickel Field Restudied. A. G. BURROWS AND H. C. RICKABY. Pp. 48, pls. 14, maps, 2. Ont. Dept. of Mines, vol. 63, part 2, 1934. 1935. The authors support a hydrothermal origin for the nickel deposits.

Soil Survey of the Roswell Area, New Mexico. W. G. HARPER. Pp. 32, fig., map. U. S. Dept. Agric., Ser. 1933, No. 2, 1936. Price, 25 cts.

The Jackson Group and the Catahoula and Oakville Formations in a Part of the Texas Gulf Coastal Plain. B. C. RENICK. Pp. 104, pls. 3, maps, 7. Univ. of Texas, Bull. 3619, 1936. Miocene to Recent stratigraphy.

Geology of Palo Pinto County, Texas. F. B. PLUMMER AND J. HORNBERGER, JR. Pp. 240, figs. 28, pl., maps, 5. Univ. of Texas, Bull. 3534, 1935. Stratigraphy, structure, oil, gas, and coal.

Grundzüge einer Pflanzenkunde der deutschen Braunkohlen. DR. FRANZ KIRCHHEIMER. Pp. 153, pls. 117. Wilhelm Knapp, Halle (Saale), 1937.

Geology and Ore Deposits of the Bayard Area, Central Mining District, New Mexico. S. G. LASKY. Pp. 144, figs. 21, pls. 11, maps, 6. U. S. Geol. Surv., Bull. 870, 1936. Price, 80 cts. Geology of lead, zinc, copper, silver and gold veins.

Informe Sobre los yacimientos de salitre de siguas de la provincia de Camaná. EDGARDO PORTARO. Pp. 156, pls. 13, maps, 4 (with appendix). Cuerpo De Ingenieros De Minas Del Peru, Bol. 113, 1935, and 113a, 1936.

The Rosebud Coal Field, Rosebud and Custer Counties, Montana. W. G. PIERCE. Pp. 177, figs. 25, pls. 14, maps, 2. U. S. Geol. Surv., Bull. 847–B, 1936. Price, $1.25. Part of a Tertiary subbituminous and lignite coal area; structure, geomorphology and descriptions of beds.

Mineral Resources of the Region around Boulder Dam. D. F. HEWETT, E. CALLAGHAN, B. N. MOORE, T. B. NOLAN, W. W. RUBEY AND W. T. SCHALLER. Pp. 197, figs. 52, pls. 14, maps, 3. U. S. Geol. Surv., Bull. 871, 1936. Price, 45 cts. Wide range of commercially valuable and accessible minerals and ores, including lead, zinc, copper, iron, tungsten, limestone, dolomite, gypsum, borates, celestite and salines. Production graphs.

SCIENTIFIC NOTES AND NEWS

J. B. Stone is opening a consulting geological practice in the west and may be addressed at 972 Linda Vista Ave., Pasadena, Calif.

E. L. Bruce has left for Scotland where he will spend the month of June with field parties of the Geological Survey of Great Britain. Later he will be official representative of the Canadian Government at the International Geological Congress in Russia.

Ralph E. Grim of the Illinois State Geological Survey has been granted leave of absence to spend several months visiting centers of clay research, particularly in Germany, England, and Holland, and studying certain clay deposits. He is also planning to attend the International Geological Congress in Russia.

Femístocles López, formerly geologist with the Chile Copper Co., at Chuquicamata, Chile, is now with the Ministerio de Formento, Caracas, Venezuela.

Reginald A. Daly of Harvard University gave 6 Harris Foundation lectures April 25 to May 5 at Northwestern University on "The Crust of the Earth."

Charles H. Behre has resigned as Chairman of the Department of Geology at Northwestern University to devote more time to research. John T. Stark has been appointed chairman in his place.

The University of Pennsylvania and the Academy of Natural Sciences of Philadelphia announce the establishment of a new four-year cooperative course in the Earth Sciences under the direction of Prof. Frederick Ehrenfeld of the Univ. of Pennsylvania. It will be offered for the first time in the Fall and will bring together two of the oldest learned foundations in America in the conduct of a program of teaching and research in geology, paleontology, and mineralogy. Opportunity for joint graduate study will also be provided.

The 5th Annual Petroleum Conference of Illinois-Indiana was held on May 29 at Robinson, Ill. The following geological papers were delivered: "The nature of favorable oil bearing structures in Pennsylvania formations in S. W. Indiana," by C. A. Malott; "The seismograph and its application to the Illinois Basin," by C. M. Boos; "The use of the new type gravimeter in detecting structures favorable for oil," by A. A. Bryan; and "Recent developments in the Illinois Basin and their significance," by A. H. Bell. Prepared discussions of these were given by W. C. Kneale, F. W. Oudt, and Verner Jones.